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**Towards an Understanding of the Way Chemistry
Students Relate to Teaching Software, Using
Stereochemistry as the Vehicle**

A thesis

submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

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ABSTRACT

The aim of the project was to identify features crucial for the effective software-based learning of chemistry. The project involved four connected studies using two methods: one developed for evaluation of student-software interaction (videotaping and stimulated recall interviewing); the other, phenomenography for investigating student conceptions related to their understanding of stereochemistry, a concept addressed by the developed tutorial.

The main insights fall into two categories: the development of chemistry educational software and teaching and learning of chemistry specifically the concepts of stereochemistry.

The original stereochemistry tutorial employed multiple representations, free navigation and model progression. Students' ideas were used to modify the tutorial. This resulted in the learning tasks covering the properties of enantiomers, using the animation and guided discovery.

The use of computers in chemistry has two advantages over the traditional educational tools. Using 3D interactive ball and stick models helped students to visualise molecules and animation assisted to visualise aspects (properties), which are impossible to observe under laboratory conditions.

Learning chemistry is strongly influenced by the way chemistry is taught. Students experienced chemistry in two worlds separated from one another - the world of body of chemistry knowledge and the world of real substances (dream world-real world concept). This insight contributes to an understanding of how learning chemistry takes place.

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1. INTRODUCTION

My experience in learning and teaching chemistry at university level began when I was an undergraduate student twenty-five years ago at Zagreb University. The way chemistry was taught to me was based upon traditional methods involving teacher-dominated transmission of knowledge.

I initially used the same methods in my teaching at undergraduate level. However, over time, I was conscious of changes of style in teaching that were influenced in part by the increasing presence of technology.

The appearance of computers has affected our society in very broad and deep ways. Computers are now present everywhere in our society, and so science education cannot avoid or ignore their ubiquitous presence. Science can now be viewed and explained using computers in ways previously unimagined, making possible entirely new kinds of learning and teaching (Marton, 1999).

While carrying out the research described in this thesis I have become aware that these changes are mirrored in the changing philosophical movements in education. The challenge laid down by learning theories, such as constructivism, involves a change of focus in the classroom, away from the teacher (as the fountain of all knowledge) to the students and the ways they construct their knowledge. However, one of the disappointing trends over the last couple of decades is that the increasing awareness of constructivist ideas by the science teaching fraternity has not been mirrored in teaching practice (Fraser, 1998) and especially tertiary practice.

The development of technology and its increased presence in science disciplines opens up new possibilities of a shift in the learning and teaching of science. The studies that investigated computer use in chemistry follow the general trend of the effectiveness of computer-based instructions as reported by meta-analysis by Fletcher-Flinn and Gravatt (1995). In the cases in which student learning of chemistry was the measured instructional outcome (as measured by tests or exams given after completion of instruction), the outcomes suggest that only moderate, if any, improvement in student learning of the experimental group has been achieved compared to the one of the control group (Wainwright, 1989; Williamson & Abraham, 1995). Therefore, there is a need to investigate the possible reasons for such outcomes in such an apparently

promising field for computer-based learning as chemistry and to suggest possible solutions that can be implemented to improve these outcomes.

The aim of the research described in the thesis was to identify features crucial for the effective computer-based learning of chemistry. The infusion of information technology into the classroom is seen as a possible catalyst for more student-centred learning. An attempt to provide such a role of computer use in learning chemistry undertaken in this thesis, included many educational assumptions such as:

- An appreciation of the knowledge that students bring along to any learning task, a key ingredient for learning theories, such as constructivism or phenomenography, described by Ausubel (1968, p. 163) as 'the most important single factor influencing student learning'.
- Learning is a very complex process and not easily explainable particularly by the traditional assumptions such as using exam marks only. Bruner's (1986) quote below applies well to the process of learning chemistry where simply examining learning outcomes conceals the richness of the learning process:

It is far more important, for appreciating the human condition, to understand the ways human beings construct their worlds than it is to establish the ontological status of the products of these processes. (p. 46)

- The nature of the discipline itself is an important constituent of the learning and teaching of chemistry, therefore it should be considered as well.
- Learning in which the use of informational technologies is employed differs from the learning using traditional educational tools. In describing the role of informational technologies in student learning, Marton (1999) highlighted that the advancements in information technology in particular "open up possibilities to bring about variation in the learning environment that have been unimaginable previously." (p. 15).
- An assumption that learning with computers cannot be compared easily with the traditional criteria for evaluating learning outcomes (DiSessa, 1987; Hattie, 1999; Reeves, 1993). There is evidence in the literature of the increasing presence of qualitative approaches used in evaluating student learning, particularly in the evaluating of computer enhanced learning of science.

These and other assumptions are reviewed in Chapters 2 - 4. Chapter 2. **Learning and**

title in index Teaching = Learning

Teaching, introduces learning and teaching at a more general level, Chapter 3 - **Learning and Teaching Chemistry** is more specific and Chapter 4 - **Computer Supported Learning and Teaching of Chemistry** is even more specific and ends with the research problem and the main research questions asked in this research.

The research methods employed in the studies described in this thesis are introduced in Chapter 5 – **Methodology**.

In the thesis two approaches, constructivism and phenomenography, both based on student learning research (Biggs, 1999), have been employed to explore learning and teaching in chemistry, with a particular focus on stereochemistry, accompanied by the use of computers. Four studies are reported in this thesis:

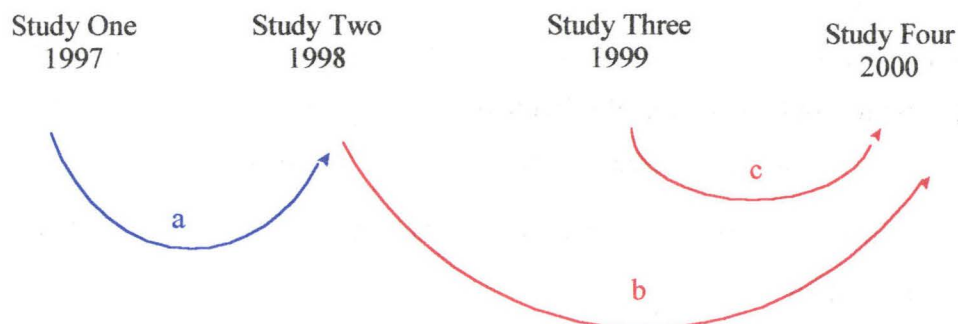
Study One - Student Use of Commercial Software in a First Year Chemistry Course. This study explored student interaction with commercial computer-based tasks available to the first year chemistry undergraduates at Massey University in 1997 (Chapter 6).

Study Two – Student Use of the In-House Developed Stereochemistry Tutorial. The study in which an in-house authored computer-based tutorial was designed in 1998 to take account of the results of Study One and the student interaction with the tutorial was explored (Chapter 7).

Study Three - Students' Conceptions Underpinning Their Understanding of Stereochemistry. A phenomenographic approach was used to explore the ways in which first year undergraduates conceptualise concepts important in understanding stereochemistry in 1999 (Chapter 8).

Study Four – Students' Responses to the Amended Stereochemistry Tutorial. This study explored the student interaction with the in-house authored computer-based stereochemistry tutorial that was revised using the findings from Study Three and Study Two respectively in 2000 (Chapter 9).

The time sequence of the studies described in this thesis is given in Figure 1.1. The curled arrows show the links between the studies. The results of Study One were used in Study Two (blue arrow a) and the results of both Study Two and Study Three were considered in the research design of Study Four (red arrows b and c).



Pavlinic, 2000

Figure 1.1. The time sequence and the links between the studies described in this thesis. The curled arrows indicate that the findings of preceded study/ies were used as a rationale for a later study.

During Study One a new method for evaluation of student use of software was developed and was employed in Study Two and Study Four respectively.

A major conclusion from Study One was that software design must take account of student learning needs as well as the subject content knowledge. An approach based on this conclusion was applied to the authoring of the tutorial. The tutorial development started in Study Two in which theories of software development and constructivist ideas were used in the authoring of the first version of the stereochemistry tutorial. Students' ideas important in understanding stereochemistry were explored in Study Three and these ideas were implemented in the second version of the tutorial, Study Four.

In Study Three, a phenomenographic approach was selected as an appropriate method for accessing students' conceptions underpinning their understanding of stereochemistry, the topic selected for attention in Study Two. The resulting hierarchy of ways students visualise molecules and the ways they link their visualisation to the macroscopic samples of compounds, as well as their stereochemical ideas made explicit the areas to be targeted in Study Four when the tutorial was amended.

One major outcome of this thesis is the insights it provides into the ways chemistry undergraduates construct their worlds of chemistry (Study Three). When the students' responses to the topic of stereochemistry as revealed in Study Three were used to revise the stereochemistry software (Study Four), the generally favourable responses to the amended software revealed the importance of taking into account students' ideas in

developing learning tasks, particularly computer-based tasks.

In addition, the use of qualitative approaches in describing student learning with computers such as employed in this thesis proved to be powerful in revealing insights of learning that take place in a student - computer task environment.

The main insights from four studies are extracted and discussed in relation to each other and to the literature in **Final Discussion**, Chapter 10.

2. LEARNING AND TEACHING

This chapter introduces the processes of learning and teaching that are part of current theories of learning and teaching in science. Apart from the description at a more general level, whenever possible attention is shifted to the aspects important in learning and teaching chemistry.

Learning and teaching are seen as very dependent and interwoven processes or dimensions inseparable from one another. It is more likely that the teaching based upon the research into student learning would provide the conditions to facilitate student learning inside institutions (schools, universities).

Analysing the research into student learning, Biggs (1999, p. 30) commented, "It is only in recent years that learning researchers have studied learning as it takes place in institutions, by students." According to Biggs "there is now a body of theory called 'student learning research' that directly relates to practice, the stands of constructivism and phenomenography being the two most influential" (1999, p. 30). Biggs pointed out that both theories put emphasis on the meaning that is created by the learner. These two theories are introduced, not only because they represent and/or are evolved from the 'student learning research' but also because of their contribution in the learning and teaching of science today.

In the description below, the educational and psychological movements that preceded, contributed to and influenced the development of these theories are discussed.

2.1. THEORIES OF LEARNING AND TEACHING

Educational and cognitive psychology as well as philosophy have so far provided science education with a number of supporting theories. In the field of education, the theories based upon student learning research, such as constructivism and phenomenography, can be contrasted with behaviourism (related to positivism or objectivism). According to Tsapalis (2001b), the behaviourism approach favoured the direct transmission of knowledge from the knowledgeable (the teacher) to the ignorant (the student). The transmitted load (the scientific knowledge) was taken to exist as an unquestionable corpus – objective, complete, precise, and invariant, independent of teacher and student. Behaviourism only provided the means (that is praise or

punishment) that facilitated or even enforced the transmission of intact knowledge (Tsaparlis, 2001b).

However, the theories contributing in learning and teaching science today (two of them, constructivism and phenomenography, described in detail below) differ from the behaviourism as they take into account the meanings as created by the learners.

Two contributors to constructivism (also seen as parts of constructivism), the Piagetian model or theory and the prior conception movement, are briefly introduced prior to the description of constructivism. Many researchers assume that philosophy of constructivism as a theory of learning and teaching grew out of the Piagetian model.

In addition to the philosophy of constructivism and phenomenography, two theories based on education psychology, with attempts to explain the possible processes that take place in a learner's memory, are also introduced. Although the psychological view of information processing is not formally the concern of the studies described in this thesis, the assumptions of these two theories are selected because they contribute to our understanding of the learning of chemistry and the learning with multimedia (information processing model/theory of working memory and dual processing theory respectively).

2.1.1. Piagetian Model

Piagetian model of intellectual development dominated science education for about two decades (1960s, 1970s and partially 1980s). Two aspects were interwoven in the Piagetian model. First, according to the Piagetian model, cognitive structures or *schema* change both qualitatively and quantitatively with increasing age and experience. Piaget identified different stages of development (sensorimotor, pre-operational thinking, concrete operations and formal operations), depending on increasing age and experience. According to Tsaparlis (2001b), not only were student stages of development or student thinking patterns considered as concrete or formal etc., but chemical concepts were also considered in the same ways.

Second, apart from the cognitive psychology's stages of development, the Piagetian model tried to explain the processes that cause the human intellectual development. By many means, the explanations of these processes match the description of learning theory.

According to Nurrenbern (2001), who named it as a Piagetian theory or a Theory of intellectual development, humans are “intrinsically motivated to grow intellectually or mentally” (p. 1108) by processes of organisation (formation of *schemas*) and adaptation (assimilation and accommodation). Assimilation involves applying an existing schema or mental structure to interpret sensory data. When it is not possible to assimilate new experience into existing schema, a disequilibrium process occurs. Equilibrium is restored by modifying the existing schema. The change of existing structures to fit newly assimilated data is called accommodation and represents construction of knowledge or a learning process (change in cognitive structure).

Piaget considered that knowledge is constructed by the individual as he/she acts on objects and people and tries to make sense of it all. Learning depends on each individual’s cognitive structure. As the cognitive structures become more elaborate, the physical environment becomes better articulated. If something is too far away from an individual cognitive structure, it cannot be accommodated, and no learning will take place. For optimal learning to take place, information must be presented in a form that can be assimilated into the present cognitive structure (assimilation means understanding). At the same time, the newly arriving information must be different enough to necessitate a change in that structure (or to cause accommodation or learning) (Hergenhahn & Olson, 1997; Wadsworth, 1989).

2.1.2. Prior Conceptions

Piagetian theory has met with strong criticism from numerous psychological researchers at least with respect to its developmental-stage component. As a result, in the eighties, many science educators and newcomers in the field opted to distance themselves from Piagetian theory (Tsapalis, 2001b). Tsapalis argues how as an alternative to the Piagetian model, researchers turned to a systematic study of how students understood scientific concepts across the school spectrum. Literature abounded with articles that dealt with chemical concepts and described students’ conceptual difficulties.

Although Piagetian theory of conceptual development was criticised by numerous psychological researchers with respect to its developmental-stage component, it was not with respect to recognition of students’ ‘existing structure’ and the adaptation or equilibrium mechanisms (assimilation and accommodation). Many authors argue that these Piagetian notions were the roots from which the movement of alternative or prior

conceptions subsequently grew (Pressley & McCormick, 1995) and they will be acknowledged later as one of the bases for the constructivist movement.

However, in the eighties there was a preoccupation firstly with the study of concepts, and secondly with the organisation of these studies into a coherent research movement. These have been variously called - alternative frameworks, alternative conceptions, student misconceptions, prior conceptions, naive knowledge, spontaneous knowledge or children's science (Driver, 1995; Pressley & McCormick, 1995). Within science education, the late Rosalind Driver was considered to be the leader of this movement (Fensham, 2001; Tsapalis, 2001b).

Students' conceptions are often inconsistent with the content they will be asked to learn in a science course and they may be highly resistant to change (Driver, 1995; Pressley & McCormick, 1995). These conceptions may have been built up over years of experience and may be consistent with other knowledge about the subject possessed by students. Students' conceptions may be so deeply entrenched that students will continue to apply alternative conceptions even after learning new science content which is inconsistent with their prior conceptions. Errant information can seem sensible even if it is not correct (Duit, 1991, as cited in Pressley & McCormick, 1995). Sometimes the students' conceptions are so strong that students simply will not believe what they see (Pressley & McCormick, 1995; Nussbaum & Novick, 1982).

Many learning theories today recognise the existence of prior (alternative) conceptions (knowledge). Prior knowledge has been described as the most important single factor influencing student learning (Ausubel, 1968).

In conclusion, both the Piagetian model and the origins of the research in prior conceptions were seen as contributors to the development of constructivism. In addition, students' conceptions underpinning their understanding of stereochemistry were investigated in Study Three. The importance of students' conceptions was acknowledged when the insights from Study Three were considered in the tutorial revision in Study Four.

2.1.3. Constructivism

A number of authors (Driver, 1995; Driver, Asoko, ^{et al} Leach, Mortimer & Scott, 1994; Kearney & Treagust, 1999) have suggested that constructivism is based upon

recognition of the prior knowledge that students bring to any learning task. This statement was used as a basis or a building core for the knowledge to be constructed, not only in the theory to explain the learning process, but also as a central insight to inform and help teachers in designing constructivist-based learning tasks (Kearney & Treagust, 1999).

The development of constructivism is based on the research of prior conceptions (Biggs, 1999, describes constructivism as a theory based on 'student learning research'). According to Biggs (1999), constructivism has a long history in cognitive psychology, Jean Piaget being a crucial figure. The paragraphs below describe the essential assumptions of constructivism and disclose how the philosophical views of constructivism and the Piagetian views are similar to each other. In another words, constructivism represents the development or extension of Piagetian philosophical views. Osborne and Wittrock (1985) claimed that Piagetian "ideas about assimilation and accommodation fit very comfortably within what has become the constructivist tradition" (p.62).

According to Tsapalis (2001b) both the Piagetian model and the prior or alternative conceptions movement should be compromised or even combined for "the benefit to be gained from an exposure to, and a use of successes of each one of them" (para.12). Thus, Adey (1987) refused to view the Piagetian theory and the prior or alternative conceptions movement as incompatible rivals, but rather thought of eventual combination of the two.

(i) Constructivism - Philosophy and Psychology

Although dating its roots back to the eighteenth century, Gruender (1996) defined constructivism as a new movement in the philosophy of education. In a few words, Savery and Duffy (1995) described constructivism as a philosophical view on how we come to understand or know, while Cunningham (1991) described how the philosophy of constructivism holds that learning is a process of building up structures of experience.

According to the constructivist view, students are not 'empty vessels' to be filled with conventional or formal science ideas. They have pre-constructed ideas, usually common within one culture and often resistant to change (Driver et al., 1994; Solomon, 1992). The authors suggested that knowledge cannot be transmitted but must be constructed by

mental activity of the learners causing conceptual change. Savery and Duffy (1995) set out three primary propositions of the philosophical view of constructivism:

- The core concept of constructivism assumes that understanding (construction of knowledge) arises from the interaction of an individual with the environment. Therefore, the individual construction of understanding (what is learnt and how it is learnt) is a function of the content, the context, the activity of the learner and the goals of the learner.
- Cognitive conflict is the stimulus for learning and determines the organisation and nature of what is learnt - the goal of the learner is central in considering what is learnt. Savery and Duffy (1995) call it 'puzzlement'; Dewey (1938) and Roschelle (1992) use the term "problematic"; Piaget (1977) and von Glasersfeld (1989) describe the need for accommodation when current experience cannot be assimilated in existing schema.
- Knowledge evolves through social negotiation and through the evaluation of the viability of individual understandings. The social environment is critical to the development of individual understanding.

(ii) Forms of Constructivism

Different authors have used slightly different names for different forms of constructivism in educational practice. According to Biggs (1999) constructivism takes on various forms: individual, social, cognitive and postmodern. Tsaparlis (2001b) considers two forms of educational constructivism: (i) personal constructivism which is associated with Piaget; and (ii) social-cultural constructivism which is linked to Vygotsky. When learning and teaching science are considered, Driver (1995) distinguishes an additional type of constructivism as a separate category. Driver offers three perspectives of constructivism; (i) cognitive constructivist, and (ii) sociocultural constructivist, but also (iii) construction of scientific knowledge, as a distinct constructivist perspective. Because Driver was considered to be a major contributor to the development of science education (Fensham, 2001), the classification given by Driver will be adopted in this thesis and these categories will be considered in more detail.

Cognitive constructivism is a form of constructivism based on cognitive psychology.

According to this philosophical view, personal construction of knowledge starts from sensory experiences about natural phenomena, and a reconstructing of these conceptions takes place as they are adapted to wider experiences (Driver, 1995). One of the models of learning and teaching based upon this philosophical view is learning by discovery.

Sociocultural constructivism (also known as social constructivism) is a form of constructivism which assumes that the individual or personal construction of knowledge (learning) is shaped in collaboration with others. Driver (1995) describes it as an interpersonal construction of knowledge. The social construction of meaning is seen as a dynamic relationship in which an interaction between the learner's personal ideas and those of others takes place and leads the learner to construct new knowledge in collaboration with others. Sociocultural or social constructivism has been influenced by Vygotsky, who emphasised both the critical importance of culture and the importance of social context for cognitive development. Therefore, learning is not seen as a purely internal process, but as a social construct which is mediated by language via social discourse (Vygotsky, 1978). The Vygotskian theory of instruction within the Zone of Proximal Development (ZPD) is probably his best known concept (Vygotsky, 1978). Vygotsky proposed that each child has a zone of proximal development where, with the assistance of a more mature partner such as a teacher or a more advanced student, the child can accomplish more and solve more advanced problems than he/she could by himself/herself. These Vygotskian views are basic to the socio-constructivist position. Under such a view, the role of the teacher changes from that of an authority figure who presents knowledge to students, to one of senior partner, or master in a master/apprentice relationship. In other words, when interacting with each other and with the teacher, the process of understanding is brought about by the opportunity for each individual to reorganise his or her own ideas through talk and listening to others. Therefore, through social interactions students are enabled to examine, compare and construct new meanings for themselves.

In summary, the principles of sociocultural constructivism assume multiple interpretations of knowledge, learning as an active process, an emphasis on the learning process as well as the end product, problem solving in real world situations, shared power by teachers and students, collaboration in the learning process, and an opportunity for students to publicly share their work and reflect on what they have

learned.

Implications of social constructivism are in student-student (peer tutoring) or teacher-student interactions. Collaborative and/or cooperative learning are models of learning and teaching based upon social constructivist philosophy and play important roles in learning science as well. McMahon (1997) described an application of social constructivism in a form of student-content interaction in which appropriate use of informational technology may be seen to connect rather than separate students from one another and provide the conditions to accomplish the goals of social constructivism (e-mail, online discussion, Internet, Network programmes, World Wide Web). The teaching support strategy scaffolding (described later in section 2.2.2. (iv)) originated in the sociocultural perspective of Vygotsky's theory of ZPD in which the cognitive development of a learner is guided by a more competent teacher, by peers or computer (a person behind an intelligent system).

Construction of scientific knowledge, a third form of constructivism (Driver, 1995), refers to the construction of science as public knowledge or *scientific knowledge* validated by the scientific community (Pines & West, 1986, name it *formal knowledge*). The construction of scientific knowledge has resulted in the scientific community sharing a view of the world involving concepts, models, conventions and procedures. Driver (1995) remarked that "learning science involves being initiated into the culture of science" (p. 395) and it is essentially a process of enculturation into ideas and models of conventional science. Scientific ideas, which have been constructed and transmitted through the culture and social institutions of science, are unlikely to be discovered by individuals through their own empirical inquiry and learning. If students are to have a chance of sharing some of the best thought-through theories that humanity has collectively generated, the introduction of students to the sophisticated conceptual repertoires and theses that have been generated within science is very important. In the learning of science, constructivism views the teacher as having a key role in introducing standard or conventional scientific views to students.

To students, conventional scientific ideas represent someone else's interpretation of the world, someone else's reality. It should be no surprise that many scientific concepts are difficult, since they represent the cumulative product of many of the brightest minds of the last several hundred years. However, once understood, with the help of a teacher, such scientific ideas are food for the student's thought in contrast with his/her own prior

ideas (Davson-Galle, 1999).

In conclusion, at all times knowledge is both social and individual, and Tobin and Tippins (1993) talk about a “dialectical relationship existing between the individual’s contribution to knowledge and the social contribution” (p. 6). Individual cognitive goals emerge through an individual’s daily participation in cultural practices. In attempting to accomplish these emergent goals, the individual constructs new knowledge linked to social and cultural life.

The recognition that knowledge has both individual and social components which cannot be meaningfully separated enabled the constructivists to construct science learning environments where multiple ways of knowing are sought and valued.

According to the sociocultural framework the social interaction between an expert chemist and learner may assist in concept development. This is where the implication of Vygotskian ZPD in which teacher (expert) - learner collaboration can be used to bridge a distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under expert chemist or teacher guidance (through a process of scaffolding) or in collaboration with more capable peers (Vygotsky, 1978). Drawing on Vygotsky’s ZPD, Bruner (1986) believes that there are areas just beyond an individual’s generative competence (hence proximal) where the learner can follow another’s activities and thoughts (those of teachers or expert chemists) without being able to construct these personally. In these zones the learner is able to use hints from others, to take advantage of others’ help in organisation, in effect, to “borrow” another’s consciousness or reflection. Through the interaction between learner’s reflective understanding and that of teacher or expert chemist, a learner is able to transform and heighten personal consciousness. The teaching art here is to help the learner transform personal consciousness without merely copying that of another.

Although the basic position adopted in this thesis assumes both individual and social components of constructivism in which knowledge is personally constructed but socially mediated (process of enculturation brought about through social interaction), in the studies described in the thesis the emphasis was given to thinking about knowledge as an individual construct. The notion of enculturation could provide a good theoretical basis for a future analysis of the data collected in this research.

(iii) **Constructivist-Based Learning**

The forms of constructivist-based learning given below are selected either because they have been employed in the studies of this thesis, or because of the contribution they have made in our understanding of the learning and teaching of science. Learning by computers as a form of a constructivist-based learning is described later in Chapter 4.

(a) *Learning by Discovery/Scientific Discovery*

Learning by discovery has a long tradition. Keislar and Shulman (1966) have suggested that learning by discovery implies diversity, novelty and unpredictability. Keislar and Shulman described how the participants who were involved in the discussion associated a range of meanings to learning by discovery. Some viewed it as experiences of individuals in which the “rule-example” method had elicited discovery experiences, others only as manipulative and something that teachers do in getting a “better pedagogy by not telling the student” (p. 27) what they know. Learning by discovery was also described as a process in which students, when confronted with a set of concrete experiences, are led to scan through a range of stored models of different kinds, a process that allows students to translate these experiences into their own language frames. In trying to fit these models to the data or problem at hand students form individual internal structures for handling the situation or problem, therefore, discovery learning was not seen as something that happens outside the learner.

Glaser (1966) has identified two dimensions that describe learning by discovery. The first involves induction or inductive teaching, or expository teaching in which a procedure involving giving a student examples of a more general case permits the student to induce the general proposition involved. The second dimension is called errorful learning and refers to the idea that in the course of discovering things for themselves, students will undoubtedly, as a result of exploring, make mistakes. The author highlighted that it is the aim to reduce the likelihood of the student making errors.

Learning by discovery found its justification in Piagetian philosophy in the 1960s. When the discussants in Keislar and Shulman’s study analysed learning by discovery in terms of a psychological phenomenon, it was suggested that construction of knowledge in discovery learning could take two very different forms, analogous to the Piagetian

distinction of assimilation and accommodation. The first is the discovery within the accepted framework, and the second is discovery which involves the reconstruction of an accepted framework and the development of a new one. It was suggested that instructional conditions should be designed to provide students with the second kind of discovery.

The justification for learning by discovery today is based on constructivist ideas (Van Joolongen & De Jong, 1997). In the 1980s and 1990s the studies that addressed learning based upon constructivism showed a shift in focus, from the description of discovery of concept or knowledge structures, toward the description of processes of scientific thought that are involved in scientific activities (Shrager & Langley, 1990; Van Joolongen & De Jong, 1997). The term “learning by discovery” was replaced with the term “scientific discovery”.

Originally, discovery learning was studied in the context of concept discovery (Bruner, 1961, as cited in Van Joolongen & De Jong, 1997), in which the main task of the learner was to find the properties of a given domain. These properties were not given directly, but had to be inferred or induced from other data (Van Joolongen & De Jong, 1997). Shrager and Langley (1990) described how the early work in this philosophical tradition focussed on the structure of scientific knowledge and emphasised the evaluating of laws and theories. However, the recent research has emphasised scientific discovery and focussed on the describing of the *processes* of scientific thought or reasoning related to scientific activities.

To provide a learner with the opportunity to construct knowledge, the learning task must be carefully chosen and well designed. Shrager and Langley (1990) listed and described a number of important activities involved in the process of scientific discovery that are approximately equivalent. These are observation, taxonomy formation (and revision), inductive law formation (and revision), theory formation (and revision), deductive law formation, explanation, prediction, experimental design, manipulation, and evaluation.

Shrager and Langley (1990) described science as “perhaps the most complex of intellectual activities” (p. 1). One of the activities of scientific discovery that is involved in learning science is exploration. Qualter et al. (1990) noted that in the traditional approach to science the aims of teaching the methodology of scientific discovery conflicted with the need to teach precise scientific laws. Therefore, it is not surprising

that initially syllabuses were dominated by content, and did not include enough exploratory activities. By examination of empirical data, the authors identified two important purposes for exploration as a way of learning science. First, exploration can bring learners to sense or experience the phenomena for themselves as vivid events, without any prior experience of the application of the theory of phenomena. Another important purpose for exploratory learning is as a means of allowing learners to sense phenomena as tangible events and thus to build up a store of experiences which can form the background for learning complex scientific concepts. By interacting with scientific phenomena learners can construct for themselves a deep and meaningful understanding of them. The authors were not advocating discovery learning of complex scientific concepts (such as Newton's Laws), but highlighted how exploration can provide the necessary concrete experience on which explanations of complex theories can be based.

In the late 1980s the most influential theory in describing scientific discovery arose from the research results of Klahr and Dunbar (1988); the theory of Scientific Discovery as Dual Search (SDDS). The SDDS claimed to be 'a general model of scientific reasoning that can be applied to any context in which hypotheses are proposed and data are collected'. According to SDDS scientific discovery occurs through two processes, a search process in a hypothesis space, containing all possible hypotheses about the system under study, and a search process in an experimental space, consisting of all experiments that can be carried out with the system.

Similarly, Pazzani and Flowers (1990) described how scientific discovery could be broken into two interacting processes. One is *hypothesis generation*, a bottom-up or data-driven process in which one proposes an explanation for some unexplained, unusual, or unexpected occurrence in terms of some causal mechanism. The other is *hypothesis evaluation*, a top-down process or a theory-driven analysis in which one evaluates a hypothesis against further data or against alternative hypotheses.

Van Joolingen and De Jong (1991) stated that hypothesis generation is a problematic issue in the discovery learning context, in particular in interactive computer simulations. The authors investigated, offered and studied the effect of different additional measures that could be added as a support for the process of stating a hypothesis (Van Joolingen & De Jong, 1991; Van Joolingen & De Jong, 1997).

Computers and Scientific Discovery

Many of the ideas about learning by discovery in science are related to learning by computers. Computers are particularly suitable tools for designing tasks to promote scientific discovery. In the world of computer-aided instruction (CAI), scientific discovery is mostly assigned to and investigated with computer-based simulations (Shrager & Langley, 1990; Van Joolingen & De Jong, 1991).

(b) Postmodern Semiotics Constructivism and Learning Abstract Science Concepts

According to constructivism the equilibrium between the individual and socially accumulated knowledge is constantly being shifted and re-established. The system is open and not predictable or finite. This constructivist approach fits the description of the post-modern movement being mirrored in education.

Lemke (1994) described postmodernism:

Postmodernism reclaims for science, and philosophy, the intellectual freedom of art. It refuses the power moves of some discourse factions that insist that their discourses are the only possible ones because they are "true". Many different discourses "work". It is not even possible to say absolutely whether many of these discourses are "consistent" with each other or "incompatible". They can be construed as being either, and usually are.

(Social Constructivism and the Construction of Meaning, para. 10)

Semiotics is the study of sign process. Cunningham (1991) suggested that the concepts of semiotics have much to offer in "conceptualising constructivism". A postmodern semiotic constructivism is a form of constructivism which is particularly suitable for justifying the learning and teaching of abstract concepts in science.

According to postmodern semiotic constructivism and Lemke (2002) "the natural language of science is a synergistic integration of words, diagrams, pictures, graphs, maps, equations, tables, charts, and other forms of visual and mathematical expression" (How Science Says What it Means, para. 3). Lemke regards every scientific concept as simultaneously a sign in a verbal semantics of discourse, an operational system of actional meanings, and usually also a visual representational system, as well as frequently a mathematical semiotic system. The great power of scientific concepts and of scientific reasoning comes from combination, integration and multiplication of meanings. In scientific reasoning one can freely and self-consistently move back and

forth between verbal reasoning, visual reasoning, quantitative reasoning, mathematical symbolic logic, and operational situated sense-making. Integration of all of these modes can allow problems to be solved that could never be solved with only one or even two of them. The modes of representation of scientific concepts such as verbal, visual, or mathematical semiotics are called the different languages of science, and Lemke (2002) concluded that teaching in multiple languages of science should also include teaching students about these languages.

Teaching Abstract Concepts

When addressing the nature of abstract concepts, Lemke (1994) asserts that “*abstract concepts* are not the sort of things to which our culture assigns much *reality* status” (Semiotics Perspectives on Learning and Abstraction, para.6). He agrees that abstract concepts refer to phenomena that exist, but raises the question of whether the ‘abstract concepts’ exist independent of the phenomena. Lemke describes them as “a shorthand way of talking about rather complex cognitive processes” (Semiotics Perspectives on Learning and Abstraction, para.6).

Lemke (1994) comments that, in cognitive theory, which promotes conceptual learning, the way to teach abstract concepts is to demonstrate how the abstract concepts apply to several different situations until the student “catches on” or generalises and “gets the concept at an abstract level” (Semiotics Perspectives on Learning and Abstraction, para.1). But, according to Lemke, even the students, who showed conceptual mastery (top grades in mathematics and physics) and were able to apply the concept in situations not too different from the ones in which it was taught, would not meet the standard of being able to apply the concept wherever it is relevant. According to Lemke (1994), common discourse of academics and intellectual culture (Driver (1995) refers to the scientific community) shapes the meanings the students have to learn. Lemke describes how teaching something by “first breaking it down into simple parts or steps” (Semiotics Perspectives on Learning and Abstraction, para.7) and then teaching the steps, is commonly used in our education system. This teaching tradition reflects the traditional objectivist philosophy that assumes that knowledge that exists can be transmitted or processed through instruction and that a given instruction causes learning (Cunningham, 1991). As the intent of the traditional instruction is to communicate this knowledge, the process of breaking knowledge into its component parts and systematically presenting the individual components to the learner is justified as

reasonable (Cunningham, 1991). But, according to Lemke (1994) the sort of reductive analysis into parts, described as the traditional teaching approach, is only possible as a post-hoc activity, or “after we have mastered the whole we can understand how it can be divided into parts” (Semiotics Perspectives on Learning and Abstraction, para.6). Lemke (1994) points out that students have to learn how wholes are conventionally analysed into parts and learn about the part-whole relationship.

According to Lemke (1994), even when teachers try their best, an abstract principle is not necessarily visible in its ‘examples’ or in the models used to describe it until students learn how these examples or models are conventionally construed as instances of the same general principle (e.g. learn to ‘see’ a phenomenon in a new way, mediated by special technical distinctions named by specific terminology; learn to see the reality the model attempts to relate to in the same way the teacher does and learn to formulate abstract generalisations; learn how to assume that the situations in which the principle applies really are ‘the same’ in some respect as those they have been taught, how to recognise and apply the principle to new and unfamiliar examples). The same is true for the scientists, science educators or science teachers in their pathway of learning science, but they have done it over time. Only after many struggles and after many years of being taught, they finally, eventually, achieved the ability to catch on, to see the inherent similarities that were there in front of them, so evident to their teachers, who similarly had themselves struggled for years to see them.

Lemke’s views of learning are related to Pressley and McCormick’s (1995) or those described by Johnstone (1997, 1999). Pressley and McCormick acknowledged how the time spent in dealing with the information plays a very important role in the learning process:

Information that is well learnt over time comes to mind more quickly than information that is not learnt well, perhaps because it has been presented in an unconvincing fashion or simply has not been presented often. (p. 365)

Johnstone (1997) suggests that “most learning probably occurs after the teaching, and sometimes many years after the teaching” (p. 46). Describing the differences in the positions of teachers and of students, he points out that teachers have two advantages, time and skills. Over the time taken for a person to move from the position of a novice learner to the position of an expert in a variety of fields, knowledge and experience are becoming inter-related in a mental network, which is rich and versatile. The mental

network enables an experienced chemist to handle the incoming knowledge efficiently.

Lemke (2002) asserts that it is the responsibility of teachers to develop the methods needed to teach all students how:

- to talk the specialized verbal language of science,
- to create and interpret the specialized visual representations of science,
- to use the mathematical and quantitative symbolisms of science,
- to execute and interpret the language of practical actions and operations that tie meanings to doings in science,
- to teach students how to explicitly integrate these different modes of representation,
- to shuttle back and forth among them,
- to reason with them in complex combinations, and
- how to communicate their ideas and results through syntheses among them.

Lemke recommended that in science education students should be exposed to scientific text instead of to science textbooks, to scientists instead of to science teachers, to scientific and technological workplaces instead of school laboratories.

(iv) Constructivism as an Educational Method

(a) *The Aim of Education*

Gruender (1996) stated that learning a portion of the knowledge humankind has already won is only a part of the purpose of education. The author argued that one of the purposes of schooling and education in general is to help students to see the previously acquired knowledge as something live and important to them. Another important function of education is to challenge students to take what previous generations have thought was knowledge and ask themselves whether it stands up to rigorous examination and testing in the experience of their own times.

In a constructivist view, the role of education is to show students how to construct knowledge (Cunningham, 1991). To achieve this, the role of education is to promote collaboration with others, to show the multiple perspectives that can be brought to bear on a particular problem and to arrive at self-chosen positions to which students can

commit themselves, while realising the basis of other views with which they may disagree. Furthermore, Cunningham highlighted that the sense of the phenomenon that is 'correct' cannot be determined independent of the context in which it appears, and that knowledge emerges in contexts to which it is relevant.

According to Gruender (1996), schooling consists of helping the students to create within themselves the constructs necessary to participate in human enterprise. Schooling helps students to figure out how to learn and critically test new constructs so they and others can consult them without being limited by the bounds of human memory. Gruender highlighted how this description bears the central epistemological truth or heart of the educational philosophy of constructivism.

(b) Constructivism - The Role of the Teacher and Instructional Design

Following a constructivist educational philosophy Gruender (1996) concluded that the proper role of a teacher is to facilitate the learning process. This can be achieved by devising situations in and out of the classroom in which students are challenged to come up with ideas to cope with the intellectual problems which are presented to them and, with their peers, to help them think these through.

Because learners must see the relevance of the knowledge and skills to their lives, the role of a teacher is in developing constructivist-based tasks (Cunningham, 1991). According to Coll and Taylor (2001), Einstein also believed that a key role of the teacher and the task given by school in teaching of science is that of motivating students for work in school and life (pleasure in work, pleasure in its results and the knowledge of the value of the results to the community).

Constructivist-based tasks should be relevant to the learner's experience (Cunningham, 1991). The teacher or instructional developer should provide access to tools that can be used to better understand or construct solutions to the problem. This can be accomplished either by the individual learner or often preferably within a collaborative group.

Cunningham (1991) regards the role of the teacher as one who moves the student from the point of completing tasks with help to independence in an ever-increasing cycle (which is in the line of Vygotskian Zone of Proximal Development). In such a situation assessment arises naturally, and the teacher is the one who is able to make the final

judgement on task completion.

Finally, it is important to highlight that within a constructivist philosophy the duty of teachers is to recognise students' prior ideas and then to take them into account in planning and performing their teaching, so that the aim of conceptual change can be fulfilled (Kearney & Treagust, 1999; Tsaparlis, 2001b).

Gruender (1996) recognised that there are many ways in which difficult educational tasks can be achieved and that we need “a knowledge of effective techniques for helping students harness their own vitality, energy, curiosity, excitement and wonder in the difficult and sometimes painful tasks of learning what they will need to know” (p. 27). While Savery and Duffy (1995) provided a clear link between the theory and the practice and presented a detailed instructional model for the problem-based learning, which developed through a constructivist framework, Gruender recommended ‘designs’ which could supply a variety of techniques in different kinds of circumstances to different learners and teachers, and these designs should be non-authoritarian and lead to a strengthening of the critical and creative abilities of students.

(v) Constructivism – The Right Choice?

As a result of the prior conceptions movement, a vast literature on students' ideas at all school ages was built up during the eighties and the nineties to the point that many followers of the movement have started to argue against the further accumulation of such data (Tsaparlis, 2001b). Further, as Tsaparlis points out, numerous attempts at correcting students' misconceptions have met limited or no success, and to many involved in science education, the situation seemed to be stagnant or even problematic.

During the last few years the criticism of constructivism as applied to science education has intensified too. According to Coll and Taylor (2001), the criticism of constructivism in the literature can be broadly classified as concerns with theoretical and philosophical basis, particularly its epistemology (i.e. the relationship between the knower and the known), and concerns with its pedagogical value which claims that pedagogy does not directly flow or is not directly prescribed by constructivism (Coll & Taylor, 2001, p. 219.). Constructivist pedagogy is based on the relativist ontology (that assumes that multiple, socially constructed realities exist, as opposed to realist ontology which assumes a single independent reality that exists outside the reference frame of the observer) and subjectivist epistemology (which subscribes relativist ontology and

assumes that knowledge is created by the investigator, as opposed to objectivist epistemology which is linked to realist ontology and assumes a researcher with observer role of the knowledge that is hard, objective and tangible).

Coll and Taylor (2001) posited two major concerns with a constructivist-derived pedagogy. One refers to the implementations of such pedagogy in large class sizes and the requirement to cover a detailed curriculum in limited time, elicitation of students' views, group work etc. which all take time, meaning less content is covered. Another major concern is the link between ontology/epistemology, and "the danger in relation to pedagogy is that such stance makes it problematic for teachers to debunk scientifically dubious theories" (p. 220), for instance creationism next to Darwinian evolution.

According to Nola (1997) the relativist ontology does not do justice to the successes of science teaching and the traditional role of the teacher as an expert instructor charged with conveying knowledge based on his or her own learning and experience to novice students in the classroom. The fact that the science content taught at the high school and introductory university level represents knowledge about which there is little disagreement within the scientific community (Millar, 1989), and the pragmatic stand of constructivists working in science education that learners' alternative conceptions and framework are important because of their significance in the learning process and not because they are equally valid alternative views of the world, make the problem even more problematic (Coll and Taylor, 2001).

A major argument in the criticism is that constructivism pays attention to how students learn (how they construct their concepts), but not to what knowledge (incorrect or correct) they construct. For example, Gruender (1996) argues that knowing that to learn anything we must create internal constructs does not tell us what the best methods for the creation of such constructs might be, and that constructivism has, so far, not done anything to solve the educational problems these factors play. He stated how "contrary to the claims of constructivism, nothing follows from this theory about what the best educational methods might be to help people learn!" (p. 26).

The next argument in the criticism of constructivism addresses the philosophical assumption of conceptual change that is supposed to happen when a student confronted with new evidence of scientifically verified ideas replaces his/her 'old' ideas with the 'new' ones. The analysis of the research on alternative conceptions by White (1999) indicated how many studies proved that there is no conceptual change in the sense of

replacements of students' views with the new ones scientifically accepted (p. 6), but rather that the new understandings are added to the old ones (p. 7). White (1999) quoted DiSessa's phenomenological position, which since 1983 advocated that there was no sudden conceptual change in which one view of the world replaces another, but a continuum of learning in which the learner gradually subsumes beliefs formed from experience. It will be shown later how these comments agree to the position of phenomenography that also advocates that gaining knowledge or learning takes place by widening experiences and not by the reconstruction of ideas (Marton & Booth, 1997).

Much criticism of the constructivist approach has arisen in relation to the assessment of student performance being based upon the teacher's subjective judgement and not objective standardised tests, which are declared to be independent of individual teacher judgement and context. According to constructivism, "objective measurement is a fiction or at best a degenerative case where knowledge is so decontextualised that only one context (the school context) is relevant" (Cunningham, 1991, p.15). Cunningham described that constructivism does not reject standardised tests, but rather assumes that these tests are just part of the educational process and that assessment is a human matter that arises naturally when instruction is embedded in situations where students are involved in realistic or actual tasks and not from an instrument designed to be as uncontaminated by the context as possible. All psychometrically sound instruments could contribute to, but cannot substitute for, teacher judgement. The teacher is the one who should gather as much information as possible through observation, talk to students and other teachers, videotapes, through tasks carried out by individuals and by groups and look at the results of the ubiquitous traditional standardised test scores. Cunningham pointed out that all gathered information provides the teachers with help in making judgements.

Cunningham also addressed the criticism related to social constructivism. It is based upon the fact that the literature on group work is full of cases where one member of the group dominates and the rest do not participate and learn very little. Furthermore, not everyone in a group learns the same thing. Some members can easily solve the problem on their own without the group, and hence learn nothing. The author stated that the traditional test given to individual group members shows the unpredictable results of collaborative techniques.

According to constructivism, the purpose of group work is not to promote the attainment of the same objective by every member. Working in groups, through collaborative or cooperative work, is likely to have the collective group objective of solving the problem. The contribution and attainments of each of the members are likely to vary widely in both amount and type, as is typically the case in real life (Cunningham, 1991).

According to Matthews (1994, 1995, 2000), constructivist approaches have neglected the role of history, sociology and the philosophy of science, aspects that are very important in promoting better teaching, learning, and curricula in science.

In conclusion, it is important to be aware of both the contribution of constructivism and its concerns in science education (Davson-Galle, 1999). Taking a conciliatory position Tsaparlis (2001b) states that most theories are not complete or perfect and that they need constant revision and improvement. They even need replacement,

But, unless a theory can explain the success of the previous one, it cannot be considered as a superior rival. At any rate, even if for some researchers various theories are conflicting, there is surely benefit to be gained from an exposure to, and the use of the successes of, each one of them. We must stay away from polemics and hostilities, but instead make efforts towards a compromise and even a combination of theories. (para.12).

So, Coll and Taylor (2001) believe that in a chemistry classroom, the best pedagogy would involve a combination of teaching by conventional transmissive and constructivist-based strategies. For teaching simple factual material, like descriptive organic and inorganic chemistry, the constructivist-based strategies would not have any advantage over the conventional transmissive strategy, while teaching about atomic structure and chemical bonding can be enhanced by a constructivist-derived pedagogy. Thus the authors found small tutorial classes well suited to interactive constructivist-based strategies for appropriate concepts.

(vi) Constructivism – Summary

This section introduced the basic principles of constructivism (philosophy and psychology, forms of constructivism, types of the constructivist-based learning that are important to this thesis, its use as an educational method and the role of teacher), but did not ignore the critics. It is important to understand teaching and learning assumptions of this learning theory as the studies in the thesis, which investigate computer-based

learning, are based upon constructivism (Learning by computers as a form of a constructivist-based learning is described later in Chapter 4). For the reason that this research is related to chemistry discipline (described later in Chapter 3), it was found that the description of postmodern semiotics constructivism, as described by Lemke, matches both the semiotics nature and the abstract nature of science discipline of chemistry. Finally a section describing learning by discovery/scientific discovery was added because of this approach being employed during the revision of the tutorial in Study Four (Chapter 9).

2.1.4. Phenomenography

Marton (1997) argues against the idea of ‘conceptual change’ in which one way of understanding a concept or phenomenon is replaced by another, more advanced understanding of the same thing. He raises the question of whether the idea of replacing one understanding with another is a reasonable description of learning and development. Marton believes that it would be “more accurate to say that in the course of learning, the learner is widening the range of possible understandings or increasing his/her repertoire” (p. 186). Marton sees a “very strong element of continuity” (p.186) in conceptual development and that conceptual changes can be seen as changes in the form or way of thinking. He explains that a phenomenon is always the experienced phenomenon and that what is learnt is variation. In Marton’s view, we learn variation and we also learn about the situation that we have never encountered before and about phenomena in ways that we have never seen before. Developing a capability for appropriating new ways in seeing means opening new dimensions of variation. Seeing learning as widening the range of experiences or variation of the same thing is the way that phenomenography explains learning.

Phenomenography has been used extensively in research on student learning for over two decades, since first introduced by Marton (1981). Phenomenography is an approach or research discipline that deals with learning as a process that enables the learner to experience a phenomenon in a way she/he has not been able to experience it previously (Marton & Booth, 1997). Booth (1997) described, from a phenomenographic perspective, how, as a result of some experience, learning is the act of shifting from not being able to do something to being able to do it. Phenomenographers have shown that students entertain a range of conceptions of learning: increasing one’s knowledge;

memorising and reproducing; applying; understanding; seeing something in a different way; changing as a person (Laws, 1996; Marton et al., 1993). Marton and Säljö (1984) described how the phenomenographic approach tries to find out why the learning outcomes differ between individuals or why the students arrive at qualitatively different ways of understanding.

Booth (1997) describes how different students can understand one and the same text, or indeed one and the same concept, in a number of different ways. A set of qualitatively different ways of understanding can be arrived at which has an internal logic (hierarchy) with respect to the meaning of the text or concept. These findings represent a cornerstone of early phenomenographic research.

The underlying philosophy of phenomenography is based on non-dualism. Marton and Booth (1997) suggest that many philosophies imposed the person-world dualism (person and what surround the person are separate, or person is on one side and independent reality is on another side) in their ways of describing the learning process. For instance, according to Marton and Booth (1997, pp. 12-13) individual constructivism is a form of cognitivism that respects the individual or 'the inner' explanations and neglects 'the outer' accounts. The authors point out how this is the reverse for social constructivism, in which "the outer" accounts such as culture are considered while the individual is not. Phenomenography does not consider person and world as being separate, rather there is an internal relation between the two. There are no individual constructions or independent realities, people experience the world or different aspects of the world and both constitute the internal relation between the two.

Phenomenography is a research approach that combines a subject-object relationship and a research method to bridge students' approaches with teaching strategies in the learning-teaching relationship. Laws (1996) described phenomenography as another of the leading approaches to the understanding of learning processes.

Phenomenography incorporates the importance of understanding teachers' perspectives on their work. According to this research approach, teachers should be less aware of the content of learning in itself, but rather as it should be understood by the learners. The nature of the teaching context and learning tasks as perceived by the learner are identified as educationally critical aspects. The teacher has to ensure that learners reveal their experience of learning in two ways. One refers to the various ways in which students understand that which is learnt, the other refers to the various ways in which

students go about (approach) the task of learning. This means that the subject of teacher reflection of learning is not only *what* is learnt but also *how* learning takes place.

According to Marton and Booth (1997), each situation, whether we consider it is a learning situation or a situation in which one is applying something learned, has a certain *relevance structure*. A *relevance structure* is the person's experience of what the situation calls for. Therefore, the teacher's role is to provide the students with tasks with a wide range of relevance structures, so that the tasks of learning can be integrated into the world that the learners experience. Hence, the relevance of the task has to be seen through personal meaning for the learner. Such kinds of tasks are more likely to provide the new ways the learner experiences the world, in other words they could cause learning.

When the learning and teaching of science is considered, Marton and Booth (1997) recognised that "there are so many built-in-taken-for-granted assumptions in the man-made world - the world of ideas such as science, as well as instruments, tools and other representations - that it is fundamentally impossible for the learner to find out about them on her own" (p. 202). They highlighted that a major task of pedagogy is to identify such critical features and focus on them by building *relevance structure* and making use of *the architecture of variation*.

To discern these 'built-in-taken-for-granted scientific assumptions' students need to be systematically helped to reflect on and change their understanding of the nature of the task, in the context in which the task is undertaken. Given a similar task in a different context, students may well exhibit a different understanding of the task, and consequently approach the task in a different way and with different outcomes.

The phenomenographic view of learning involves changes in the person-world relationship that implies pre-existent knowledge or experience. In the phenomenographic model, we do not face phenomena as such, but the phenomena as described by others, in terms of patterns of a shared culture through a shared language. Our own world becomes increasingly the world of others as well. This is an important difference from individual constructivism in which knowledge is regarded as being an individual construction - *within* the individual (or with social constructivism, which sees the social, the cultural, the situational *outside* the individual as the fabric of knowledge)(Marton & Booth, 1997).

(i) Phenomenography-Based Research - Contribution in Understanding of Learning – Teaching Relationship

The contribution of phenomenographical research has been recognised in the wider educational society (outside phenomenography). For example, constructivist Biggs (1999) in the book “Teaching for Quality Learning at University” acknowledges that the phenomenography-based research on approaches to learning contributed a great deal to improving learning. Furthermore, the terms such as deep or surface approaches appear throughout this thesis, therefore there is a need to describe the origins and meanings of these terms.

For that reason, out of the broad range of the research based upon phenomenography done in the last twenty years, the aspect that addresses learning approaches and learning outcomes was selected to illustrate the contribution of this research discipline in understanding the learning - teaching relationship.

(a) *Approaches to Learning and Learning Outcomes*

Booth (1997) described how early phenomenographic studies led to three important insights into student learning. The first insight into student learning has been described previously (section 2.4.1. Phenomenography), and involves a set of qualitatively different hierarchically ordered ways/categories of understanding a phenomenon. The second insight discerned two qualitatively different ways in which students go about, or approach, the task of learning (Booth, 1997). One is a deep approach, which is distinguished by a search for meaning in the text or concept; another is a surface approach, which instead focuses on the words comprising the text or concept (Marton & Säljö, 1976; Marton & Säljö, 1984). The third insight disclosed that the process of learning and the learning outcome are logically or internally related and are not separate entities (Booth, 1997). Booth reported that students who adopted a deep approach achieved an overwhelmingly superior understanding of the message of the text and also retained information better than their surface-studying colleagues. A study by Prosser and Trigwell (1999) recognised how teachers’ approaches to teaching have the elements similar to those identified in students’ approaches to learning. Prosser and Trigwell suggested a close relationship between the approaches to learning students adopt and their teachers’ approaches to teaching.

Biggs (1999) reported that western educators distinguish between rote learning and meaningful learning, types of learning as classified by Ausubel (1968). According to Biggs, a deep approach to learning would most likely lead a student towards meaningful learning, while a surface approach would lead towards rote learning. It has long been known that students' learning depends in part on the effort they put into their work. The studies on deep and surface approaches resulted in identifying a third, achieving or strategic approach (Biggs, 1987; Entwistle 1995), which is used in conjunction with a deep or surface approach to learning. Repetitive learning as a form of learning is associated to memorisation and not so easily distinguished from rote learning (Biggs, 1999, p. 127). However, Biggs (1999) and Marton, Watkins and Tang (1997) also suggest that the strategic use of repetition may lead to 'deep memorisation' and meaningful learning. The role of memorisation in learning and understanding (learning as understanding was identified as the most advanced category in which students describe/experience learning) has been identified among Chinese learners (Marton, Watkins & Tang, 1997). The interpretation of the ways in which Chinese learners experience learning showed a close relationship between memorisation and understanding, a relationship known as the "Chinese paradox". Namely, these students see memorisation and understanding running in parallel directions, to substitute each other, unlike the ways in which Western European students assign memorisation to a rote learning or surface approach to learning (Marton, Watkins & Tang, 1997). Biggs (1999) also states that a common misconception is that memorisation indicates a surface approach. He points out that sometimes, verbatim recall is wholly appropriate, such as when learning lines for a play, acquiring vocabulary, and learning formulae. Memorisation becomes a surface approach when it is used instead of understanding or to give the impression of understanding.

The Biggs's discussion above is important in understanding the use of memorisation in learning chemistry. From one point of view the use of memorisation seems appropriate when students need to learn formulae. From the other point of view, the use of algorithms in solving problems in chemistry without conceptual or meaningful understanding is an example of inappropriate use of memorisation. Such an inappropriate way of the use of memorisation can be assigned to rote learning or a surface approach to learning.

Biggs (1999), an advocate of constructivism, admits how constructivism and

phenomenography have a lot in common and that “the most basic commonality is that meaning is not imposed or transmitted by direct instruction, but is created by the students learning activities, their ‘approaches to learning’” (pp. 12-13). He suggests that the concepts of surface and deep approaches to learning are very helpful in conceiving ways of improving teaching and that good teaching should encourage appropriate learning activities that comprise the deep approach to learning (Biggs, 1999). If, for instance, teachers are aware of how students approach their learning, they are able to design the instruction that better meets these processes.

Although good teaching supports the deep approach and discourages the surface, according to Biggs (1999), much of traditional practice, for a variety of reasons, has the opposite effect. Biggs states that deep and surface approaches are not personality traits (are not fixed characteristics of students or their ‘academic personalities’) as is sometimes thought, but reactions to the teaching environment. Biggs offered the ‘3P’ model, which depicts the classroom as an interactive system in which student characteristics and the teaching context mutually determine deep or surface learning activities, which in turn determine the quality of learning outcomes. The 3P model of teaching and learning (Biggs, 1999) includes three points in time at which learning-related factors are placed: **P**resage, before learning takes place (student factors and teaching context); **P**rocess, during learning (learning-focussed activities); and **P**roduct, the outcome of learning.

(ii) Phenomenography – Summary

Phenomenography was introduced because this research discipline is applied in the study which explored students’ conceptions related to stereochemistry (Study Three, Chapter 8). The section that introduced learning approaches was introduced to inform about the terms used in this study, but also to demonstrate how the contribution of phenomenographical research broke the boundaries of one theory and became applicable in a more general educational sense.

2.1.5. Information Processing Model for Learning (Theory of Working Memory)

Johnstone (1997, 1999) pointed out the relevance of the information processing theory

for the learning of chemistry. Johnstone (1997, 1999) believes that the information processing model for learning, based upon the “work of psychologists, educators, artificial intelligence workers, and dealers in common sense” (1997, p. 262) can explain the mechanisms of human learning. According to Johnstone, events, observations or instructions are perceived by human senses as sensory signals, which all enter a perception filter. There is a link between the perception filter and long-term memory (LTM). The stimuli or information we admit through the perception filter passes into a working space or working memory where it is held and manipulated before being rejected or passed on for storage. A number of processes take place in working memory such as interpreting, rearranging, comparing, storage and preparation, all aimed to make sense of the information. Sense is something that fits or adds to what we already know and believe. Therefore, there is an interaction between what we already hold in long-term memory and how we handle new information. This interaction provides a link between LTM and working memory. Finally, LTM represents the storage of information, sometimes branched, sometimes as separate fragments that we hold as our knowledge and beliefs and is used subsequently in working memory.

Working memory has been identified as the critical point in the information processing model for learning, and most difficulties in learning are associated with working memory functions (Johnstone, 1997). Johnstone described working memory as “a limited shared space” (1997, p. 263) in which two functions are competing for that space: to hold information; and to process it into a form that can be used or stored. Quite often too much information causes the overloading of working memory and prevents processing. The limitation of working memory is experienced in a lecture when according to Johnstone (1997) the student’s entire working space is “devoted to transferring the spoken words to notes and very little or no understanding takes place at the time” (p. 45.). Johnstone associated problems in learning chemistry with teaching chemistry in which the working memory of a learner cannot cope with the “simultaneous assault especially when much of the information is intangible” (1999, p. 46).

The importance of the information processing model of learning and the limitation of working memory are the basis for the teaching strategy chunking that is described later in section 2.2.2. (iv).

(i) Dual - Processing Theory

The rapid escalation of the use of multimedia in our teaching-learning environment and in our everyday lives in general, has encouraged educational psychologists to elucidate more about the nature of multimedia learning. One model that is useful in explaining the information processing that takes place in the use of multimedia in learning science is dual – processing theory (Williamson & Abraham, 1995).

The assumption of dual-processing theory, also called dual - coding theory, is that human working memory consists of verbal working memory and visual or imaginal working memory. Under the dual - processing theory, we use words and pictures that activate both visual and verbal codes. Hartley (1994) stated that verbal and visual representations of some concepts dually coded are more memorable than those coded verbally only or visually only. On the other hand, the verbal codes for pictures are more available than the visual codes for words, therefore pictures are more likely to be dually coded than the words (Paivio (1986) as cited in Williamson and Abraham, 1995). Dual coding has historically been seen as a way to explain why memory for pictures is better than memory for texts. According to Dobson (1999) the cognitive sciences assume that graphic representations are seen as computationally more effective in communicating material. Several concepts were used to describe this phenomenon. According to one concept, the semantically related parts of a diagram are likely to be located near to each other; according to another concept, by coding information in diagrams, new information often becomes visible. Finally there is an aspect suggesting that diagrams are pedagogically useful because graphical language is easier to process (Dobson, 1999). It is most likely that all of the different explanations contribute towards a better understanding of the processes described by the dual - processing theory.

Investigating the image modes in chemistry, Kleinman, Griffin and Kerner (1987) cited Albert Einstein's letter to the psychologist Jacques Hadamard, in which one of the greatest minds in science described the power of the visual over the verbal codes in his own abstract thinking:

The words of the language, as they are written and spoken, do not seem to play any role in my mechanism of thought. The physical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be voluntarily reproduced and combined.

...

The above mentioned elements are, in my case, of visual and some of muscular

type. Conventional words or other signs have to be sought for laboriously in a secondary stage, when the above mentioned associative play is sufficiently established and can be reproduced at will.
(Kleinman, Griffin & Kerner, 1987, p. 769)

So, it seems that some scientists, such as Albert Einstein, start from their own image about a phenomenon and produce a description of it in the form of words as a final result. If this is so, then one of the possible problems in learning and teaching science in a regular classroom would be the teacher's expectation that students, once given a verbal description of the phenomena, can easily operate in an opposite process (from words to images) and form an image from description given in words (imagine it) as scientists do. The diagram in Figure 2.1. suggests the different pathways of the processes used by a scientist and a learner respectively in understanding a scientific phenomenon.

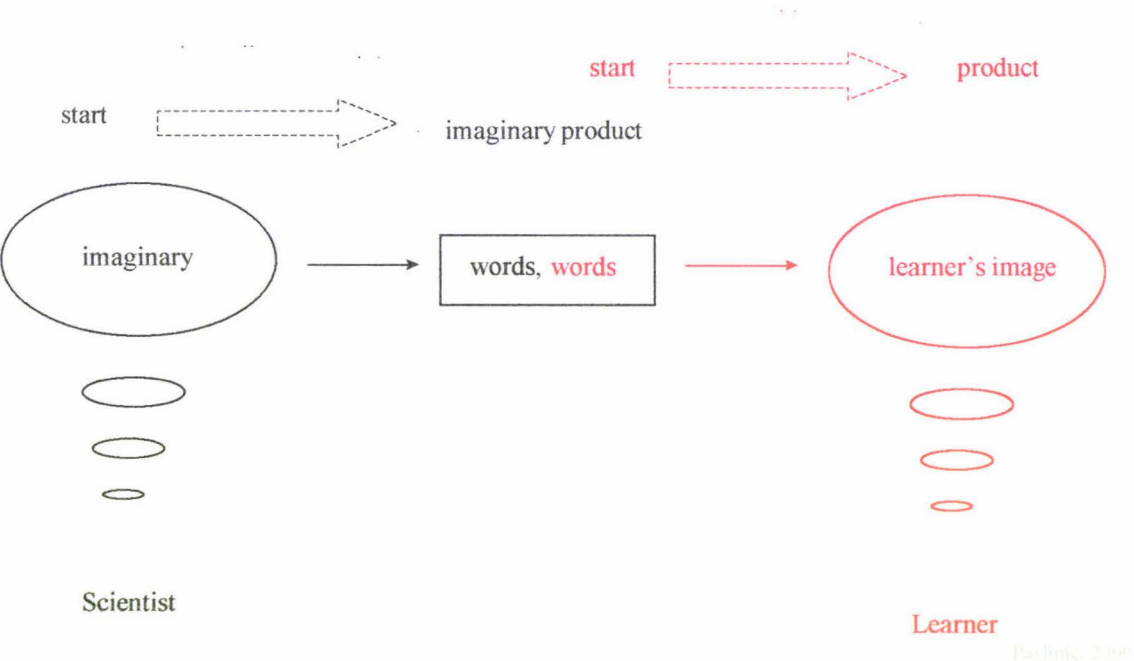


Figure 2.1. Possible learning difficulties in communicating science ideas.

A scientist starts from a visual (or imaginary) mode as a source and produces words as his/her imaginary product. These words are approved by the scientific community and are used in the science curricula. On the other side is a student who is supposed to learn about it in a classroom. The mismatch occurs when students are mostly instructed using words only and asked to use these words as a source to produce vision or images that should fit the vision (images) of scientists. The meaning of the words as the outcome of the scientist's thought cannot easily lead the student to images that are the same as those

of the scientist. It seems obvious that the visual codes or images and not just verbal codes, if used in teaching science, would provide students with better science instruction and help them in their understanding of scientific ideas.

Paivio (1986) (as cited in Williamson & Abraham, 1995) highlighted that pictures are superior as learning tools because verbal codes for pictures are easier to produce (or more available) than visual codes for words and the pictures are much more likely to be dually coded. Therefore, when compared to the verbal codes, dynamic pictures or animation may trigger the formation of deeper coding. Advocating multimedia learning Hartley (1994) quoted findings already known in the early 1970s of our superior memory for pictures: "A five-second exposure of each picture in a series, followed by a recognition recall test, produced performances of greater than a 90% correctness even when the number of pictures exceeded 2500." (p. 77).

The use of computers made a shift from static graphical representations to dynamic and interactive representations, which enabled objects to be moved by the learner in the learning environment. Dynamic diagrams turned out to be a visual language, understood with a minimum of textual comment. Dobson (1999) asserted that these opened diverse new frames in learning-teaching research, from issues relating to aspects of domain and the level of representation to new theories applied to learning with interactive graphics.

A number of authors advocate the multimedia learning of science because dual presentation modes, such as text and illustration or speech and animation are more likely to stimulate deep or meaningful learning than single-mode presentations, such as verbal modes only, that are mostly present in traditional instructions (Williamson & Abraham, 1995).

Multimedia learning offers not only words and dynamic pictures or animations, but audio as well. A study by Mayer and Moreno (1998) explored multimedia learning in which two animations were tested, accompanied either with concurrent narration or with concurrent on-screen text. Two experiments involved 78 and 68 college psychology students respectively, a questionnaire with a retention test (recalling relevant steps in any experiment process), a matching test (choosing the correct names for elements in illustration) and a transfer test (generating answers to problems that require applying the learning to a new situation). The authors found that across both experiments students who could listen to the narration describing the major steps during the task, outperformed in all tests those students having the on-screen text involving the

same words. They concluded that multimedia learners could integrate words and pictures more easily when the words are read aloud rather than written. Mayer and Moreno declared that working memory includes an auditory working memory and a visual working memory, each with a limited storage capacity. They suggested that both the animation and text are coded in the visual working memory and that narration or sound is coded under the auditory working memory. The process of selecting, organising and integrating the information in each store results in better retention of information and hence promotes meaningful learning.

When compared to constructivism, the information processing model explains the learning process from a different perspective. Tsaparlis (2001b) argues that the integration of multiple and often different theories/strategies/perspectives rather than testing one against the other is more likely to bring better understanding of the learning itself. Models with attempts to combine different theories have been described in the educational literature. Freyberg and Osborne (1996) described generative learning as an alternative suggested by Wittrock (1974), a view of learning with a proposition that “learners must themselves actively *construct*, or *generate*, meaning from sensory input; for example, sights, sounds, smell and so on “ (p. 82). Wittrock has combined his ideas about generative meaning with some ideas from information processing psychology to produce a generative learning model (Osborne & Wittrock, 1985). Therefore, the generative learning model incorporates aspects of both the constructivist and information-processing traditions of cognitive psychology. In Osborne and Wittrock’s view “the generative learning model is centrally concerned with the influence of existing ideas on what sensory input is *selected* and given *attention*, the links that are *generated* between stimuli and aspects of memory store, the *construction* of meaning from sensory input and information retrieved from long-term memory, and finally the *evaluation* and possible *subsumption* of constructed meanings” (p. 64). It is similar to information processing theory with its emphasis on processing information, but goes further on the generation of new conceptual understandings. Constructivism parallels and directly complements the generative learning model in considering the learner to be active processor of information.

To conclude with Freyberg and Osborne’s (1996, p. 85) view: “Any model of learning unavoidably incorporates some gross oversimplification and no model is likely to be useful in helping us to take into account all the complexities of the process.”

(ii) Information Processing Model - Summary

The information processing model is introduced because many educators use this model in describing learning chemistry. The dual-processing theory also contributes in understanding of learning with computers, as both words and images play an important role in processing information.

2.2. TEACHING TO FACILITATE LEARNING

This section emphasises the teaching of science. Laws (1996) who addressed the learning and teaching of science from different perspectives quoted Ramsden's (1988) statement that the main, if not the sole purpose of teaching, is to facilitate learning. As an introduction, the process of teaching science, as assumed by the theories of learning and teaching, is summarised again (although already described in Theories of Learning and Teaching at the beginning of this chapter). Then, teaching to facilitate learning is addressed from the point of view of the role of a teacher as a facilitator of the teaching process.

Hattie (1999), in a paper in which he analysed influences on student learning, highlighted the role of the teacher and its significance in relation to other contributors that influence student learning:

It is clear that structural and social influences are minor, what the student brings in terms of achievement and disposition to learn are powerful, teaching process are paramount, and the teacher methods are there - this must lead to the conclusion that, yes teachers make the difference, but only teachers who teach in certain ways. (Hattie, 1999, Television, para. 21)

Student learning will be most likely to occur if teaching science is based upon 'student learning research', the cornerstone on which the theories of learning and teaching, such as constructivism and/or phenomenography, were built. Two teaching approaches, a constructivist-based approach named "teaching for conceptual change" and a phenomenography-based teaching approach named "teaching by bringing about variation", are briefly described below.

Teaching for Conceptual Change

Because the construction of knowledge usually involves both individual and social processes (Driver et al., 1994), teaching for conceptual change assumes relationships of

both processes.

Science educators are increasingly convinced that new formats, other than the traditional lecture with or without a demonstration, must be developed (Pressley & McCormick, 1995). When science content is taught, students often find scientific ideas challenging and difficult to understand. Some students learn little while others cannot apply what they have learnt. A number of interventions have been introduced aimed at conceptual change. Pressley and McCormick (1995) indicate that a student first needs to be aware of his or her belief and that more than just cognitive conflict is necessary for cognitive change to take place. Students often need quite a bit of convincing before they give up a prior conception that appears correct to them in favour of a new one. According to Pressley and McCormick, effective instruction needs to produce clear dissatisfaction with errant belief and provide an intelligible, fruitful and plausible alternative conception. Such an alternative is likely to provide obvious intellectual power not permitted by the prior conception (Posner et al., 1982).

Teaching by Bringing About Variation

According to phenomenography, variation is an appropriate teaching approach, which if used when introducing scientific phenomena should bring the students new experiences and provide learning. Variation provides the students the opportunity of experiencing simultaneity in discerning a certain phenomenon, i.e. having in focal awareness different aspects of a certain phenomenon at the same time (Marton & Booth, 1997).

Learning described as gaining knowledge about the world, means developing the capability to experience a certain phenomenon even when it appears in novel situations. To enable the learner to become capable of discerning aspects of the phenomenon in a way other than the ones she/he had been capable of discerning before, means to provide the focal awareness of other aspects or more aspects of the phenomenon than was previously the case. This is the teacher's role. The teacher should provide the learner such a variation (relevance structure of a situation) that might enable the learner to change her/his experience or to experience the phenomenon in a more complex or more advanced way (Marton, 1999).

Teaching by bringing about variation could more likely enable the learners to deal with the situation in an unknown future, in situations they have never seen before and which cannot be defined in advance (Marton & Booth, 1997). Marton (1997) explains:

If the students are dealing with a narrow range of problems in their studies, the likelihood of their being able to deal with other kind of problems in relation to which their studies are potentially relevant would be much less than if they had encountered more variation. (p. 184)

and

.. the more narrow the range of situations, problems, appearances of phenomena, points of view, perspectives, that we have encountered in our studies are, the less likely it is that we will be capable of dealing with novel situations, new appearances, other points of view, other perspectives. (p. 196)

In addition to the philosophical background to teaching science, two additional factors that contribute to teacher effectiveness in facilitating learning are described:

1. The teacher's knowledge of both content and pedagogy - Pedagogical Content Knowledge – PCK (Shulman, 1986)
2. The strategy a teacher employs in his/her teaching - Teaching Strategies (Ramsden, 1992), which matches the pedagogy dimension of PCK.

2.2.1. Pedagogical Content Knowledge (PCK)

Pedagogical content knowledge contributes to teachers' effectiveness in facilitating learning chemistry..

Pedagogical content knowledge was first introduced by Shulman at a national research conference on the study of teaching in Austin at the University of Texas in 1983, and was developed as a part of teaching theory and today its acceptance is advocated by many researchers and educators, particularly those interested in learning and teaching science. As the term suggests, PCK assumes mutual interaction of two categories – subject content knowledge and pedagogy.

Shulman (1999) reminded the readers of his lecture entitled “The Missing Paradigm in Research on Teaching”, given at the conference mentioned above, when most participants were shocked to hear him declare that the missing paradigm was the study of subject-matter content and its interaction with pedagogy. He pointed out that the concept of PCK was “welcomed in higher education circles because it buttressed the claim that teaching, like research, was domain specific. This implies that teaching as ‘the transformation of understanding’ rested on depth, quality and flexibility of content knowledge and on the capacity to generate powerful representations and reflections on

that knowledge” (p. xi). Shulman (1999) hopes that those who agree with these ideas now will, in the future, give more attention to the “connections between teachers’ knowledge and the ultimate consequences for students’ learning and development” (p. xi).

Fensham (1999) described how the 1980-90s have seen a redirection and reinvigoration of research on the pedagogy of science, and how the content of school science was an issue needing attention from researchers in addition or in association with pedagogically focussed studies.

According to the Glenn Report (2000) science teaching at primary or secondary school levels and science teacher’s development in the USA has focussed on process knowledge or pedagogy, despite a general weakness in science content knowledge of many science teachers (Fensham, 1999; Glenn, 2000). Two separate categories, conceptual knowledge and process knowledge (pedagogy) with the emphasis on the latter one, have dominated the educational system within the Anglo-American tradition. The lack of emphasis on content knowledge has been identified as teachers’ weaknesses in science knowledge (Fensham, 1999; Shulman, 1986). Shulman (1986) pointed out that only the content knowledge can enable the teacher to transform the subject-matter knowledge into forms accessible to the students, because the teacher is not only a master of procedure but also of content and rationale and capable of acting /enacting and explaining why something is done.

The recognition of teachers’ weakness in science knowledge in the USA informed that the subject content was a missing category of teachers’ PCK. However, later in the 1990s, the research turned attention to the university level, which in most cases identified pedagogy or process knowledge as a missing category of PCK.

Addressing the learning and teaching of chemistry at university level, Coppola (1996) described the difficulties that arise because of the underlying assumption that the subject matter expertise of a faculty member is a necessary and sufficient requisite to good teaching. Coppola (1996, Conclusion, para.1) commented that the ”subject matter mastery is the beginning, not the end of effective instruction”. He acknowledged that “the deeper and more elaborate teachers understanding is, the more it will allow them to pick up and choose among the variety of situations they know of in order to create a situation that will make this understanding accessible to students” (para. 3). However, Coppola also acknowledged that progress in the practice of teaching arises from the

synergy derived from knowing pedagogy as well as knowing the subject matter, chemistry for instance. Coppola (1996) highlighted that a teacher's ability to understand student understanding is crucial in order to effectively help students understand specific subject matter.

To realise the task of transforming the subject-matter knowledge into forms accessible to the students (Shulman, 1986), teachers need to know a multitude of particular things about content that are relevant to its teachability (Bucat, 1999). Bucat (1999) specified that the term PCK refers to knowledge derived from the interaction between pedagogical beliefs and characteristics of the content in order for teachers to decide how a particular topic might be presented for optimal 'learnability'. It refers to knowledge about the teaching and learning of particular subject matter, taking into account its particular learning demands.

Van Driel et al. (1998) tried to demonstrate that there is no universally accepted conceptualisation of PCK. Referring to what they call practical or craft knowledge these authors described it as a knowledge that encompasses teachers' knowledge and beliefs with respect to various aspects such as pedagogy, students, subject matter and the curriculum and also guides the teachers' action in practice. Elaborating on Shulman's work, Van Driel et al. (1998) stated that PCK as described by Shulman (1986) encompasses every category of knowledge which may be relevant to teaching, but that the craft knowledge, as teacher's integrated knowledge, represents "teachers' accumulated wisdom with respect to their teaching practice" (p. 674). Van Driel et al. assumed that PCK is an essential component of craft knowledge, so it can be used effectively and flexibly in the communication process between teachers and learners during classroom practice. In their view, the value of PCK lies essentially in its relation with specific topics, so PCK has to be discerned from general pedagogical knowledge on one hand, and from the subject-matter knowledge per se on the other. Therefore, teaching strategies used should refer to a specific topic and not in a way that purports general applicability. In their empirical study on teachers' PCK of a specific topic, chemical equilibrium, they described how the design of workshop and experimental course was used to enhance chemistry teachers' PCK with respect to this topic. From the craft knowledge perspective, instead of generating a checklist of effective instructions, this workshop, in which 12 chemistry science teachers were involved, provided the teachers with opportunities to develop their craft knowledge in different

ways. Gaining a knowledge base enables the teachers to teach specific topics effectively and flexibly in situations that are subjected to different contextual, situational and personal influences. It seems that their understanding of craft knowledge that incorporates PCK is very similar to the understanding of PCK, as described by Bucat (1999).

Pedagogical content knowledge involves a mutual integration between two categories. It includes an understanding of what makes the learning of specific topics easy or difficult. The importance of this integration has been recognised in the continental European tradition since 1958, when Klafki's didactic analysis on the core of preparation of instruction, was first published (Klafki, 1995). Klafki recognised that preparing lessons is the place where the interactive relationship between theory and practice, fundamental to all education, must be concretised in the form of reflective decisions for planning instruction and learning. He introduced the didactic analysis, a process needed to turn primary sources of knowledge, like the science discipline, into knowledge for schooling, i.e. learning (Fensham, 1999).

To conclude, at high school level there is a need for teachers to develop their content knowledge, while at university level where academics have always been teachers there is a need to develop teaching expertise. Biggs (1999) highlights the academics' responsibility for the body of knowledge that underwrites good teaching and refers to Ramsden (1992) who described university teaching:

The professional authority of the academic-as-scholar rests on a body of knowledge; the professional authority of the academic-as-teacher should rest on a body of didactic knowledge. This comprises knowledge of how subjects he or she professes is best learned and taught. (p. 9)

(i) PCK – Summary

In designing the stereochemistry tutorial both aspects, the content knowledge and the pedagogy, were considered. In the initial stage of the tutorial development (Study Two) apart from the content knowledge, an alignment of the educational theory constructivism with the design of the tutorial was employed. For example, in the tutorial design, a model of increasing complexity was employed. Initially a student was given simple problem tasks and gradually as the student progressed through the tutorial the complexity of the tasks increased. That way of instruction was educationally adopted in

teaching most chemistry concepts.

However, much more pedagogy was considered in Study Four when the tutorial was revised in a way that the students' conceptions (Study Three) and comments (Study Two) were taken into account.

2.2.2. Teaching Strategies

One of the forms in which teachers demonstrate their pedagogy is the strategy employed in their teaching. Ramsden (1992) reviewed research in teaching and derived three generic ways of understanding the role of the teacher in higher education. The strategy the teacher employs in communicating subject content with an aim to facilitate student learning has corresponding implications for the way students are expected to learn (and the author talks about the theories of teaching in higher education). To avoid the confusion with the theories of learning and teaching (e.g. constructivism or phenomenography) that were previously described in this chapter, the term teaching strategies appears more suitable than the term teaching theories for this discussion.

(i) Teaching as Telling or Transmission

Much of the folklore of university teaching follows the line that teaching undergraduates involves the transmission of content or the demonstration of procedures and skills. The view of students as "passive recipients of the wisdom of a single speaker" (Ramsden, 1992, p. 111) seems to be unproblematic, as long as the speaker is an expert in the subject matter. The main focus is on the teacher, and the quantity rather than the quality of the information which gets across to students is used to measure learning. This approach assumes that the quality of the learning and the responsibilities of the learner remain outside the sphere of the lecturer, the program or the university. Studies have shown that such superficial engagement by students with content leads to a surface rather than to a deep approach to studying. Modern applications of this approach employ computer-assisted learning or video presentation, to enable faster transmission of greater amounts of information.

(ii) Teaching as Organising Student Activity

In this approach teaching is seen no longer as just the telling about, or transmitting of

subject knowledge. Rather the focus has moved away from teacher towards the student being engaged in the learning activity and teaching is now seen more as supervising and organising of activities. According to this strategy, the use of efficient procedures that make students active should ensure student learning. Such techniques are those that promote class discussion or processes that require students to link their theoretical knowledge to their experience. Student learning is no more just the individual learner's responsibility.

According to Ramsden (1992), teachers who employ this teaching strategy give emphasis to a development of a new teaching technique rather than to a change of their understanding of learning. For that reason, many attempts at innovative teaching at university level involve staff development in learning of new teaching techniques.

(iii) Teaching as Making Learning Possible

Bruner (1966) recognised that “knowing is a process” rather than a product and that the knowledge acquisition requires both learner and teacher to participate in the process. According to this conception of teaching, students and the subject content to be learned are linked together. Teaching is seen as teacher – student cooperation that provides the conditions to make learning possible. To help students learn, teaching involves finding out about students' conceptions and intervening to improve or change them, if identified as misconceptions. This approach has been recognised by the cognitive psychologist David Ausubel (1968) who stated:

If I had to reduce all of educational psychology to just one principle, I would say this: the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly. (p. 163)

Teaching also involves creating the context of learning in which students are actively engaged with the subject matter. It means that a student's prior knowledge, misconceptions and the content to be taught direct the ways and methods a teacher uses. Learning is seen as something that the learner does when modifying his or her ideas. This approach of teaching provides the students with the possibility of developing and applying a deep approach, rather than a surface approach to learning.

Improving teaching is an integral part of this strategy and is seen as an open developing process that involves continual reflexive activity by teachers. Such activity includes teachers being aware of context-related specific circumstances, individual differences

between learners, the nature of subject matter as well as the range of misconceptions or alternative conceptions that arise when students reflect on a given topic (for a review of research on student alternative conceptions in chemistry and implications for teaching and learning see Garnett, Garnett, and Hackling, 1995). Therefore, different and not predetermined ways of helping students to change their understanding are taking place in different learning situations (environments).

In conclusion, it is assumed that good and committed teachers do teach in a way that is student-focussed and which provides conditions that make learning possible (i.e. development or changing of conceptions). However, Ramsden (1992) argues, "it might be that good teaching is more common, and perhaps even easier to achieve in some subject areas than others" (p. 118). Ramsden (1992) states that the teaching strategies *teaching as telling or transmission* (labelled (i) above) and *teaching as organising student activity* (labelled (ii) above) are more often present in those subject areas which "typically receive lower student ratings such as engineering" (p. 118). The most likely reason is the nature of the subject or the content to be learnt. Pressley and McCormick (1995) suggested that in many cases science instruction does not permit learning that is sufficiently extensive and meaningful. This means that teachers teach without having their students learn. In reviewing research that relates to undergraduate science education, Laws (1996) finds that the concepts of science have proved difficult to teach effectively. The students' science conceptions and their learning approaches are influenced by the ways in which knowledge is structured and presented to them (Laws, 1996; Ramsden, 1993; Shepard & Gilbert, 1991). According to Ramsden (1993) different teachers frame different curricula for students. In a real sense, they teach different things and students learn different things from them.

(iv) Teaching Support Strategies

Teaching strategies, which aim either to organise student activity or make learning possible, usually involve different support strategies, two of which are selected and described because of their importance in teaching in technology-based environments.

(a) Scaffolding

Scaffolding is a teaching technique, strategy or instruction that provides support to allow a learner to learn for him/herself.

Initially, the term scaffolding was used to describe certain kinds of support which learners receive in their interaction with experts, teachers, mentors, or skilful peers. The most common form of learning has been apprenticeship and was explicitly related to Vygotsky's sociocultural perspective and the concept of the zone of proximal development (ZPD). According to ZPD the actual developmental level of the learner is compared with the level of potential development that can occur with guidance or collaboration with a more competent person.

The term scaffolding refers to a dynamic process reflecting teacher adjustments of the task or context based on student responses, both cognitive and affective. Cognitive scaffolding has been defined as what a teacher does when working with a student "to solve a problem, carry out a task, or achieve a goal which would be beyond his unassisted efforts" (Wood, Bruner & Ross, 1976, p. 90), but Flick (1998) also highlights the importance of teacher's affective orientation.

McLoughlin (1999) described how originally, the teacher's role was conceived as providing scaffolding assistance through modelling (demonstrating tasks, skills and concepts), contingency management (recognising and rewarding learner actions), feedback (which enables students to compare themselves to others) and cognitive structuring (learners are assisted to organise their own thinking). Verbal scaffolds such as questioning and cognitive structuring enabled learners to organise their own activities and made a shift from teacher-supporting to self-regulating position.

However, according to McLoughlin (1999) scaffolding or the mechanisms for assisting learner cognition through the ZPD have been extended greatly by practical applications in technology-based environments, in which learners attain new skills concepts and knowledge provided by a tutor or intelligent agent.

A form of verbal scaffolds in which teachers and learners occupy the same space and are face-to-face engaged in learning processes in the social context of a conventional classroom with its prescribed rules, roles and explanations McLoughlin (1999) described as asymmetric scaffolds. The teacher was regarded as an expert and the student as a novice. The form of teacher questioning students has been shown to be a form of social control. In technology supported environments the concept of scaffolding includes new forms of support, with increased responsibility for students and a fading directive of asymmetric aspect of scaffolding. New forms of support include scaffolding embodied in the information, such as prepacked material on the Internet, visual cuing

and simulations, separate web pages of direction on what to notice or what process to employ, tutorials that are interactive or downloadable, help pages, additional explanatory links or communication forms to contact the instructor or peers (Bull et al., 1999).

(b) Chunking

Chunking is described either as an instructional strategy that promotes cognitive development (Persichitte, 1993) or a method of organising information (Feifer & Tazbaz, 1997).

Chunking principle applies to the effective communication of information between human beings and is found particularly useful in the domain of written communication (reading, spelling, literacy or acquisition of vocabulary). A Harvard psychologist Miller put the concept of chunking forward in the 1950s. Miller (1956) suggested that entire information cannot be processed simultaneously and that working memory can retain, at most, only about seven plus minus two chunks of information at one time. A chunk is any meaningful unit. Since then the concept of chunking and the limited capacity of working memory became a basic element to cognitive psychology, the information processing framework and all subsequent theories of memory. Today the concept is also described as a method for a good human-computer interface design (Feifer & Tazbaz, 1997).

Chunking is based on psychology of information processing model of learning (Theory of working memory). Information processing model of learning (see section 2.1.5.) suggests that working memory (also called short term memory) plays a central role in sorting and manipulation of information.

Chunking is aimed at organising or breaking information down into units or meaningful “chunks”, so the working memory is dealing with a limited number of “chunks”. Johnstone (1999), who tries to explain learning chemistry through the information processing model, selected first, time or experience of “cca 10000 hours of study and practice” (p. 46) and second, a skill called “chunking” as two main advantages that teachers do and learners do not have.

Chunking is important in designing educational software. A designer, who is free from the linear sequence of pages can organise a complex network of chunks (text, animations, graphics) in which each chunk may point to several other chunks.

(v) Teaching Strategies - Summary

In conclusion, the teaching strategies, introduced above, are examples that demonstrate how teachers adopt different pedagogies when assigning the subject content knowledge into a form accessible to student. The teaching strategies that were introduced can find justification in adequate learning and teaching theory. While the strategy (i) – teaching as telling or transmission can be supported by the traditional teaching theory (behaviourism), the strategies (ii) and (iii) can be supported by constructivism. An attempt undertaken in designing stereochemistry tutorial in Study Two considered the teaching strategy (ii) – teaching as organising student activity and involved teaching support strategies scaffolding and chunking. The organised tasks in the tutorial aimed to engage students in learning activities. However, after the students' conceptions related to stereochemistry (Study Three) were considered in the tutorial revision (Study Four), the revised tutorial also included the elements of strategy (iii) – teaching as making learning possible.

2.3. SUMMARY

The approaches undertaken in the studies described in this thesis are based upon constructivism (Study One, Study Two and Study Four) and phenomenography (Study Three), and do not explicitly consider the information processing that may take place as these experiences or constructs were formed.

The two theories of learning and teaching science, constructivism and phenomenography, both based on 'student learning research', highlight the fact that the learning and teaching of science are not separate processes, but rather interwoven and dependent on each other. Being aware of student learning research has been identified as the way of aligning teaching that will more likely produce the desired learning (Biggs, 1999). In addition, two theories based on cognitive psychology, information processing model and dual-processing theory, are also introduced because of their contribution to the understanding of how learning of chemistry and how learning with multimedia may take place, which are both addressed in the studies described in this thesis.

Knowing what students need to improve their learning is not the same as knowing how to help them. In a study that analysed the ways of improving teaching by studying

learning. Ramsden (1988) discusses how it cannot be denied that the results of research, when applied to the classroom context, produced some important results. However, these often appear more as diagnostic tools (for example, describing the characteristics of the different approaches a student might take to learning), rather than ways to overcome problems (for example, no prescriptive advice on how to alter the approach is provided).

Where the learning of science is concerned, both constructivism and phenomenography highlighted the important role of a teacher. Hattie (1999) analysed the influences on student learning and considered the contribution of many constituents but highlighted the role of a teacher and its significance in relation to other contributors that influence student learning. According to Hattie the teacher is the one who “makes a difference” in student learning.

Apart from being aware of the student learning process (pedagogy), teachers should master the content to be introduced to students. Both characteristics are equally important and constitute the teacher’s pedagogical content knowledge (PCK).

The effective teacher with his/her PCK employs the teaching strategy which engages students in learning activities, or attempts to teach in a way that makes learning possible. These teaching strategies involve support strategies such as scaffolding and chunking which encourage students to discover, learn and love any subject, including chemistry!

3. TEACHING AND LEARNING CHEMISTRY ✓

Teaching and learning of chemistry cannot be examined without understanding of teaching and learning in general. That was why Chapter 2 considered learning and teaching at the more general level, while this chapter focuses on specific application in chemistry.

The theories of learning and teaching, constructivism and phenomenography, which are described in Chapter 2, assume that learning and teaching are connected processes, so the subject content to be learnt, in this case chemistry, is also an important factor and a constituent in the process of learning and teaching chemistry.

Therefore, in this chapter, a description of chemistry as a science discipline is included with a discussion of the difficulties in learning that arise from the nature of chemistry, as well as a description of the teaching methods used to address difficulties in learning chemistry.

3.1. SCIENCE DISCIPLINE – CHEMISTRY

Pressley and McCormick (1995) discuss how the understanding of most of the topics in science requires higher-order thinking skills that are less likely to be developed in other disciplines. Also, investigations of student learning in the classroom have shown that scientific concepts, which are constructed, validated and communicated through the cultural institutions of science, are unlikely to be discovered by individuals through their own empirical inquiry (Driver et al., 1994). Learning chemistry as a science discipline thus involves being initiated into conventional scientific ideas and practices and making these ideas and practices meaningful at an individual level. If the teaching is to lead students toward conventional scientific ideas, then the teacher's intervention is essential, both to provide appropriate experimental evidence and to make the cultural tools and conventions of the science community available to students.

The sections that follow introduce and discuss different aspects of chemistry, namely conceptual demands, language and spatial visualisation, all with an aim to reveal what makes chemistry difficult to learn and teach.

3.1.1. Chemistry - Intrinsic Nature of the Discipline

(i) Multiple Nature of Chemistry – Johnstone’s Triangle

Difficulties in understanding chemistry have been recognised and ascribed to its multiple nature in which the macroscopic, symbolic and microscopic dimensions of chemistry must be connected to bring about an understanding of a phenomenon (Gabel, 1999; Johnstone, 1991, 2000).

Johnstone (2000) talks about a model which has to do with the nature of chemistry. He suggests that chemistry exists in three forms which can be thought of as corners of a triangle. No one form is superior to another but each complements the other. These three forms of the subject are (a) the *macro* and tangible: what can be seen, touched and smelt; (b) *submicro*: atoms, molecules, ions and structures; and (c) the *representational*: symbols, formulae, equations, molarity, mathematical manipulation and graphs (initially, in 1991 the author used terms macro, sub-micro (particle) and symbolic). According to Johnstone (2000) some of the problems in learning chemistry are due to the fact that most things which we encounter in the world, and from which we form many of our concepts, are macro in nature. However for chemistry to be more fully understood, the learner must move to the micro (the author uses the term submicro) situation where the behaviour of substances is interpreted in terms of unseen molecules and ions and recorded in some representational language and notation. Johnstone describes how this is at once the strength of chemistry as an intellectual pursuit, and the weakness of chemistry when teachers try to teach it, or more importantly, when beginners (students) try to learn it. Professional chemists keep these three dimensions in balance and are able to switch from one to another or use all of them simultaneously, but this is rarely possible for the learner, especially the beginner learner.

Johnstone (1999) noted that chemical educators usually assume that all forms of the subject chemistry must be taught simultaneously. The author pointed out how “psychologically this was probably a disaster” that causes the overloading of the working memory during information processing (the Information Processing Model for Learning is described in Chapter 2). Johnstone (1999) described how, in chemistry, our senses cannot help us to form the concept of element or compound, atom or molecule, electron or proton and that chemists are operating in an intellectual area very different from our senses. Such chemical concepts are not tangible in a way that most of our

concepts are tangible. The author mentioned that, even at graduate-level, students tend to handle only two of macro, micro and symbolic languages at a time.

(ii) Abstract Concepts of Electrons, Atoms and Molecules

Chemistry is a discipline built on a model of a microscopic world of electrons, atoms and molecules. These abstract concepts of atoms or molecules have been investigated, especially in studies exploring the particle nature of matter. Many chemistry educators recognised the importance of understanding the particle nature of matter, for instance, Krajcik (1991) described it as critical in learning chemistry.

A literature that explores the relationship between student understanding of the particle nature of matter and learning chemistry suggests that student understanding of the particle nature of matter develops over time spent in dealing with chemistry. Stavy (1995) found that students from Grade 8 and over (ages 13 and over) start to apply the particle theory of matter. She recorded a gap of two years between the time students are taught the particle theory of matter and the time they spontaneously apply it, for example to define the term gas. Students also failed to understand some important aspects of this theory (Benson, Wittrock & Baur, 1993; Gabel, Samuel & Hunn, 1987; Stavy, 1995). While students applied the particle theory to explain gaseous state (intuitive idea), they did not apply it to explain solids and liquids, which are counterintuitive ideas (Stavy, 1995).

Even at the university level, only moderate results were obtained. A study of Gabel, Samuel and Hunn (1987) revealed that 50% of university students ignored the orderliness of particles and concluded that students' conceptions of the particle nature of matter are often far from the accepted scientific ideas.

A study by Benson et al. (1993) revealed that only 8% of students at the Grade 2-4 level were able to represent the nature of gases using the particle model. At the university level the number of students using the particle model had increased to 85%. However, according to the authors mentioned above, only 37% of university students showed particles in an approximately chemically correct particle distance distribution.

In a study that involved 23 high school students as a control group and 20 and 23 students respectively in two treatment groups, Gabel (1993) showed how, when the particle nature of matter was emphasized in instruction, student understanding of

chemistry increased, not only on the microscopic level, but also on the macroscopic and symbolic levels. Gabel (1993) suggested that chemistry could be taught and understood better if the kind of instruction that students receive ranges across the threefold nature of chemical phenomena. In a recent study, Gabel (1999) discusses how chemistry instruction predominantly uses the most abstract, symbolic nature and that the symbols are often ambiguous. According to Gabel, this can lead to incomplete student visualisation and to inadequate understanding of the symbolic models of molecules. Gabel pointed out that a student must be capable of associating particles with models or analogies in order to understand the microscopic nature and that the models must be associated with symbols.

The importance of student understanding of particle nature of matter and the role it plays in student reasoning was revealed also in Study Three (Chapter 8), as a part of study which investigated student conceptions.

3.1.2. Chemistry - The Scientific Language

Another factor that also influences a student's ability to master the abstract ideas of electrons, atoms and molecules is the type of language used. Chemists use a series of precisely defined terms, such as stereoisomer, diastereomer or other terms to help describe ideas relating to the shape of molecules. Students must master the language in order to develop and communicate the chemical concepts.

The link between the language of academic science and the nature of classroom language has attracted attention for a long time (Lynch, 1981; Lynch, Benjamin, Chapman, Holmes, McCammon, Smith et al., 1979). Lynch et al. (1979) investigated the ability of high school students (Grades 7 to 10) to recognise simple definitions of concept words associated with the theme, the nature of matter. They also investigated the effect of variables (such as age, gender, IQ and socioeconomic status) on scores. Among the findings, the study revealed that students have great difficulty with the description of 'volume'. According to the authors, verbalisation of simple but important reference concepts such as gas/liquid/solid is often neglected in classroom and laboratory dialogues. 'Ion' had the lowest recorded score for all items at Grade 7, but reached the same level as 'molecule' at Grade 10 (60% of students). Finally, from concepts relating to the substructure of the atom, the meaning of the word electron in science revealed that students associated it with electrical current rather than subatomic

particles. A study by Lynch (1981) involved a post-test only research design with 1635 pupils of Grades 7 to 10 (969 boys and 666 girls). The concept words of all grades were categorised at different levels of meaning or thinking styles and named Membership, Partial association and Generalisation. The author found that the relative percentage of students' responses placed into the category Generalisation increased with the grade. Lynch highlighted that this change in students' thinking style needs to be recognised by teachers who can choose the quality of instruction and the content at the particular grade.

Ebenezer and Erickson (1996) pointed out that students should be made aware of the differences in the meanings based upon their everyday talk and the meanings embedded in chemist's language. For example, in everyday language the word 'particle' refers to a very small, visible piece of solid substance such as a granule of sugar. Likewise, chemical meanings of words such as solution or reduction differ from their everyday language meanings.

According to Laws (1996), language is an often ignored factor in the learning and teaching of science. The research suggests that scientific language has to be learned along with scientific concepts and that it is usually never taught explicitly. This may mean that the learning of scientific concepts is rendered more difficult because they are couched in a characteristic but alien language.

The use of everyday language in a scientific context is an issue for teachers who try to make scientific ideas more familiar to students, and for students who are not familiar with scientific language and use the everyday language instead. The use of everyday language in a scientific context has been identified as a potential source of students' alternative conceptions (Presley & McCormick, 1995).

Laws (1996) identified the correct use of scientific language as a crucial feature in gaining understanding. Although Johnstone did not include chemistry language in his macro-micro-symbolic triangle, the role of language in understanding chemistry should not be neglected. If an understanding of scientific language of chemistry is added as 'a crucial feature' in gaining understanding of chemistry to the model of understanding chemistry through the macro-micro-symbolic triangle developed by Johnstone (1991), the added dimension of scientific language makes this complex model of understanding chemistry even more complex. But, the research reported above confirms that language does play a very important role and should not be ignored in teaching and learning

chemistry. Pavlinic, Buckley, Davies and Wright (2001) suggested that the use of scientific language, which communicates between and integrates the threefold nature of chemistry, should be included into Johnstone's triangle as shown in Figure 3.1.

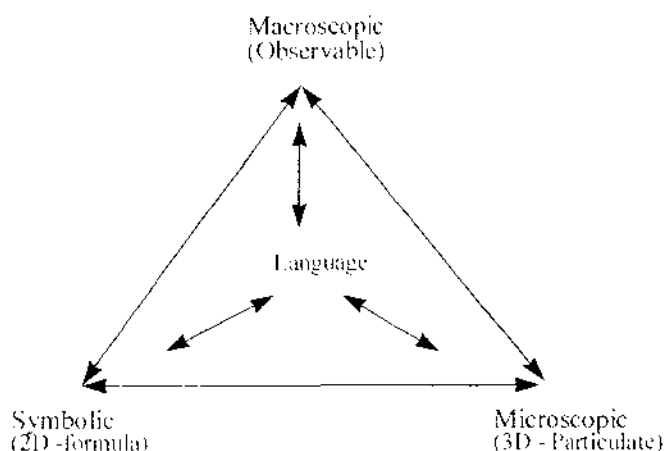


Figure 3.1. The threefold nature of chemistry integrated by the use of language.

Johnstone's triangle of chemistry is supported by Lemke's (2002) postmodern semiotics constructivism in which Lemke talks of different modes of representation or different languages of a scientific concept such as verbal, visual, or mathematical semiotic system. The integration of these modes can allow problems to be solved in a way that could never be solved with only one or even two of them. Lemke also asserts that the role of education is to teach students about all the different languages in science, their meanings and their use.

The sections described above revealed that from one viewpoint, the multiple, mainly abstract nature of chemistry, which is included in the macro-micro-symbolic triangle of Johnstone's description of chemistry and from another viewpoint, the chemistry language, are integrated aspects which make chemistry difficult to learn. Also, Johnstone's macro-micro-symbolic triangle was used as a frame of reference in discussion and analysis for most of the results obtained in the studies described in the thesis (Studies Two – Four).

3.1.3. Chemistry - Spatial Visualisation Requirements

One of the greatest chemists of this century, Robert Burns Woodward (1917-1974) was awarded the Nobel Prize in 1965 for his “meritorious contributions to the art of organic synthesis” (Marton, 1997, p. 192). Woodward (as cited in Marton, 1997, p. 192) described that the scientific achievement of this scientist was made possible by his remarkable ability

... for visualising three-dimensional structures. It was as though he could move, in his mind, among these structures, viewing them step-by-step, their pathways toward new possibilities and eventual targets. (C.E. Woodward, 1989, pp. 241-242)

Three-dimensional visualisation has been recognised as a relevant and important skill required for chemistry (Tuckey & Selvaratnam, 1993). This is born out by a number of articles reporting a significant positive correlation between spatial visualisation and achievement in chemistry (Bodner & McMillen, 1986; Carter, LaRussa & Bodner, 1987; Pribyl & Bodner, 1987; Tuckey & Selvaratnam, 1993). In a review Tuckey and Selvaratnam (1993) describe how many students who failed a visualisation test also failed chemistry and suggest that spatial visualisation tests could be used to predict success in chemistry.

In a study carried out by Pribyl and Bodner (1987) two spatial ability tests, the Purdue Visualisation of Rotation (ROT) test and the Find-A-Shape-Puzzle Figures (FASP) test were given to subjects in four organic chemistry courses. Regularly scheduled exams were used to measure chemistry performance. The results of their study suggested that students with good spatial abilities were better at problems that required ‘understanding’ of the problem, but there were no significant differences in the answering of questions that required rote memorising or the application of simple algorithms.

The ability to visualise molecules in three-dimensional space is particularly critical for the organic chemist. The three-dimensional translation of a molecule from a drawing to a conventional projection has been reported to be the most problematic step for students (Barta & Stille, 1994). Barta and Stille suggested that the degree of success involved in simply rotating or flipping the molecule in one’s mind and then drawing the compound again is proportional to the experience of the viewer. For novices, this endeavour is

frequently overwhelming.

In a review by Eliot and Hauptman (1981) it is stated that earlier studies established that mental rotation of an object *per se* is an important source of spatial difficulties. Later studies have established that spatial ability involves the interaction of two major factors, *spatial orientation* and *spatial visualisation*. *Spatial orientation* is defined as the ability to remain unconfused by changing the orientation in which visual stimuli are presented. *Spatial visualisation* is defined as the ability to mentally manipulate pictorially presented stimuli by a process which involves recognising, retaining and recalling configurations in which there is movement of the figure or parts of the figure (Carter, LaRussa & Bodner, 1987; Eliot & Hauptman, 1981; Lord, 1985).

Studies that compared gender related achievement in tasks that require spatial ability have shown a clear gender related difference in spatial visualisation, with males outperforming females (Eliot & Hauptman, 1981; Golbeck, 1986; Staver & Halsted, 1985). This difference could be due to different reasoning processes or to a different attitude to science tasks by males and females (Linn, 1982; Staver & Halsted, 1985) or due to females demonstrating a lack of understanding of the context rather than lacking spatial ability (Golbeck, 1986; Ingham & Gilbert, 1991). Eliot and Hauptman (1981) on the other hand found from their studies that females performed mental rotation more slowly on the task, but no less accurately than males.

First-year university chemistry courses require a competence in handling three-dimensional concepts and it has been suggested that such skills should be taught in order to achieve effective learning and understanding of chemistry concepts (Tuckey & Selvaratnam, 1993; Tuckey, Selvaratnam & Bradley, 1991). These skills are not specifically taught in most school or undergraduate chemistry courses, it being implicitly assumed that the required skills will be 'learned along the way'. Research evidence, however, strongly indicates that a good proportion of students in most courses are not confident in using these skills (Tuckey, Selvaratnam & Bradley, 1991).

There are many studies showing that visuo-spatial ability can be enhanced through interactions with the environment and through carefully constructed learning sessions (Lord, 1985; Noh & Schermann, 1997; Shubbar, 1990; Tuckey, Selvaratnam & Bradley, 1991). Well-known Euclidean spatial problems (for example Piagetian water level and plumb line tasks) are often used to test the principle of horizontality or verticality (Eliot & Hauptman, 1981; Golbeck, 1986). Several remedial instruction programs have been

developed to identify the nature of and reasons for difficulties associated with three-dimensional thinking and for improving three-dimensional thinking skills in chemistry (Lord, 1985; Shubbar, 1990; Seddon & Moore, 1986; Seddon, Tariq & Dos Santos Veiga, 1984; Tuckey & Selvaratnam, 1993, Tuckey, Selvaratnam & Bradley, 1991).

A study by Lord (1985) involved spatial exercises that required the participants, eighty-four college undergraduate students enrolled in a college major's biology course, to mentally bisect three-dimensional geometric figures and to envision the shape of the two-dimensional surface formed by the bisection. The effect of the intervention on student's cognitive processing of spatial information was tested by pre-test post-test comparison of visuo-spatial problem solving. The results showed that statistical improvement in spatial visualisation and spatial orientation (significance of 0.05 or higher) did occur for the experimental group.

Shubbar (1990) used six types of remedial programs for 96 high school boys, aged 15-16 years, who showed difficulty in visualising rotation from molecular diagrams. Each program consisted of models rotating with one of three different speeds, and either with or without shadow prompts. The post-test scores of the experimental and control groups showed that all programs brought about a significant degree of learning but there were no significant differences in improvement of understanding of rotation in molecular models between the programs used.

To teach the visualisation of reflection or rotation using diagrams, in pre-university science courses at two colleges, Seddon et al. (1984) selected 20 students for an experimental and control group at each college. The authors administered student practice and direct training in visualising one of the following types of transformation, reflection across the XY-, XZ- or YZ- planes or rotation about the X-, Y- or Z-axes. The post-test scores showed that all six programs were successful in teaching the particular task, but had not improved any learning in terms of applying the knowledge of reflection across a different plane or rotation about a different axis. In a later study, where the students were in the age group 14-15 years and where the sexes were almost equally represented, Seddon and Moore (1986) tried to determine the structure of abilities underlying the visualisation of rotation about three Cartesian axes for three-dimensional structures presented as plastic models or diagrams. The authors argued that the ability to visualise rotation in diagrams is not related to the ability to visualise rotation in models, the two types of tasks seeming to be psychologically distinct and

highlighted the role of teacher in helping the students to make this relationship. They concluded that the most effective method to help students to visualise rotation was one that involved students simultaneously viewing models actually rotating.

Tuckey, Selvaratnam and Bradley (1991) tested 31 second-year undergraduate chemistry students (20 males and 11 females) at the University of Bophuthatswana for their competence in three-dimensional thinking skills. They employed pre-tests and post-tests and the split-half analytical method and identified the nature of three-dimensional thinking skills (tested by standard items). Difficulties with three-dimensional thinking were attributed to student incompetence in just a few relatively simple concepts and skills. They also found that a two-hour remedial workshop program, introduced to one experimental group, was sufficient to improve student performance significantly.

The spatial visualisation is described as particularly important in understanding stereochemistry, a topic addressed in the in-house authored tutorial (Study Two). A summary below integrates this difficulty with the difficulties described earlier in describing stereochemistry.

3.1.4. Stereochemistry - Abstract Concepts, Spatial Requirements and Scientific Language

One of the topics that occurs early in the university organic chemistry course, stereochemistry, is a critical marker of a student's future success in the subject because mastery of stereochemistry involves the ability to visualise and mentally manipulate molecules. This skill underpins the rest of modern organic chemistry and much of biochemistry. The terms used in stereochemistry such as isomerism (introduced for the first time at Year 12 in high school) that have to be learned along with the stereochemical concepts cause additional difficulties for the students.

At the start of this research there was not much literature examining the difficulties in learning stereochemistry, and further investigation is warranted. Chemistry teachers, however, have identified stereochemistry as a difficult topic for students (Barta & Stille, 1994; Black, 1990).

Some chemical ideas have been explored widely, not only among a large number of students of the same generation, but also throughout the age range, from early

childhood to the high school or university level. Ideas about light, evaporation of water, electric current, air or states of matter are present to children from the earliest ages (Osborne & Freyberg, 1985) and the development of children's ideas of such topics over time has been explored.

Stereochemistry has however been poorly investigated possibly because it appears only at late stage at high school level (Year 12, Year 13), and is mainly taught at university level. A study by Schmidt (1992) is one of rare studies in this area, which investigated students' concepts of isomerism with 7441 senior high school students Grades 11-13. The results indicated that students are inclined to restrict their concepts of isomerism to components belonging to the same class of compound. Most examples of geometric isomers or stereoisomers that are presented by structural formulae in their textbooks always seemed to the students to be very similar, a fact that caused great confusion. For example, the study uncovered that students were not able to distinguish structural isomers from stereoisomers.

At high school, students become familiar with ideas closely related to stereochemistry such as three-dimensional visualisation, molecular geometry or shapes of molecules (according to Morrison and Boyd, 1992, 'structure in three dimensions is called stereochemistry'). Understanding molecular geometry and shapes of compounds underlies the understanding of the spatial arrangement of different stereoisomers.

A study by Tuckey and Selvaratnam (1993) reported that a large proportion of chemistry students have difficulty with the three-dimensional thinking problems they encounter in their courses, both at high school and at university level. This indicates that a study involving students' understanding of stereochemistry should involve a test of students' spatial abilities.

An earlier study by Peterson and Treagust (1989) explored alternative conceptions of covalent bonding and structure by grade-12 students. This study revealed that while 78% of students were able to demonstrate an understanding of the principles of the valence-shell electron-pair repulsion model (VSEPR model), subsequent test items revealed how weak their understanding really was of its application to problem situations. Garnett, Garnett and Hackling (1995) reviewed students' alternative conceptions in chemistry, including covalent bonding, molecules and intermolecular forces. The authors also found that the determination of molecular shape using the VSEPR model was particularly difficult for students. While students have shown

understanding of the principles of VSEPR model on one test item, 74% failed to correctly apply the model to identify the structure of particular molecules. Furthermore, familiarity with the shape does not necessarily lead to understanding of the isomeric possibilities. In a study on isomerism mentioned earlier, Schmidt (1992) revealed that although students did not expect isomers to be of the same shape, they still had problems identifying the isomeric possibilities.

Very little research has been done exploring students' ability to verbalise concepts of stereochemistry. In a study by Lynch et al. (1979), that addressed the concepts related to understanding stereochemistry, students have shown difficulty describing 'volume' or concepts such as gas, liquid or solid. Already mentioned Schmidt's study (1992) pointed out that the use of *scientific language* plays an important role in understanding the concept. For example, the iso-nomenclature for branched hydrocarbons can lead students to identify isomers only by branched carbon chain as they are presented in their textbooks (e.g. isobutane instead of 2-methylpropane). With a limited number of simple examples describing each term that was presented in their books, students practised applying the term to the very narrow range of isomeric possibilities.

Although the research mentioned above explores students' conceptions about abstract concepts of atoms and molecules, molecular shapes and the use of scientific language at high school level, very few similar investigations have been carried out at tertiary level.

In summary, the features of stereochemistry that are challenges to learning for students include:

- Stereochemistry requires spatial visualisation (the term itself alludes to this requirement);
- Still most of the instruction and problem solving tasks (e.g. present in textbooks, written exams) related to stereochemistry are given in a form of 2D symbolic structures;
- The use of physical (concrete) molecular models was identified in helping visualising rotation, but not much research was done on the effectiveness of their use in addressing different stereochemistry concepts;
- Not much of instruction at the observable (touchable) level is present in learning and teaching of stereochemistry;

- Stereochemistry is described by using language alien to the students (e.g. enantiomers, diastereomers).

Therefore, there is a need for more research in learning of stereochemistry including investigation of students' conceptions related to stereochemistry at the tertiary level.

(i) Learning and Teaching of Stereochemistry

Stereochemistry is built up on the abstract concept of atoms, arranged in three-dimensional space. Furthermore, stereochemical terms must be learnt to accompany these abstract models and also three-dimensional visualisation abilities are needed for success. These abstract concepts have to be introduced at schools or universities.

The terms describing stereochemistry concepts are very specific and a definition of each term is connected with its meaning. For example, by knowing the term enantiomers does not assume a student understands that enantiomers are “stereoisomers that are nonsuperimposable mirror images” (definition taken from 23.101 Chemistry I (a) Study Guide, Massey University, in 1997). In addition, the understanding of the meanings of other terms used in definition, such as stereoisomers or nonsuperimposable, is needed as well. In stereochemistry, the understanding of the concept has to be assigned with the appropriate terminology. Therefore, for learning of stereochemistry, the connection of the term or label with the conceptual understanding is needed.

Many chemistry concepts are connected (interrelated) in a way that an understanding of one concept can be linked to understanding of another concept. Students with a good background of concepts related to stereochemistry (e.g. molecular shapes) are more likely to understand the concepts of stereochemistry with less difficulty and to learn and associate new terms compared to those who have a poor background and who need to learn both the concepts and the associated terms.

According to Driver (1995) and Driver et al. (1994), this kind of scientific knowledge has to be constructed through an active learning process. Gruender (1996) argued that contrary to the claims of constructivism, “nothing follows from this theory [constructivism] about what the best educational methods might be to help people learn” (p. 26) (see also Chapter 2, Constructivism - The right choice?). The author acknowledged that there “is ample evidence that some elementary skills can be conveyed in an authoritarian fashion through demonstration and repetitive practice, and

the machinery we need for the exercise of higher intellectual and creative functions may depend on the earlier mastery of more elementary skills" (p. 26). It might be that the case of learning of abstract stereochemistry concepts fits into this category (see also Coll & Taylor, 2001).

Lemke's (1994) explanation of learning abstract concepts, based upon postmodern semiotic constructivism, can be applied to learning stereochemistry. Lemke explained how in academic education, it is assumed that students can learn abstract principles by induction from examples and by descriptions of abstract properties and relations, but the author himself is not convinced that this works. According to Lemke, an abstract principle is not necessarily visible in its 'examples' or in the models used and students have to learn how to see the imaginary properties of examples or models that are presented to them. Lemke pointed out how the time spent or experience gained over the years has a crucial role in dealing with abstract concepts. So, it is no surprise to find, both from the educational literature and the results of the studies reported in this thesis, that student conceptions about chemistry phenomena do not necessarily match those introduced by the teacher or given in the textbooks.

In order to effectively apply any particular model to the learning of stereochemistry concepts students have to be taught the meaning of each model or example employed; they have to be taught how to apply the model in a new situation and they should get an opportunity to practice the use of different models/examples in order to understand the message the model/example shown is supposed to deliver.

The phenomenographic approach tries to find out why the outcomes differ between individuals or why the students arrive at qualitatively different ways of understanding (Marton & Säljö, 1984). From the phenomenographical point of view, in learning stereochemistry students need to be introduced to different ways of seeing, representing and understanding of stereochemical concepts. Then, they need to be systematically helped to reflect on and widen their understanding. Given a similar task in a different context, students may well exhibit a different understanding of the task, and consequently approach the task in a different way with different outcomes. Therefore, the role of the teacher's instruction is very important. The study described by Schmidt (1992) showed that, to solve isomeric problems, students recalled examples solved in their textbook, associated with the term. With a limited number of simple examples describing the term, they focussed on a very narrow range of isomeric possibilities.

This section considered the descriptions of the learning theories constructivism and phenomenography in teaching and learning stereochemistry. It is suggested that stereochemistry is likely to be a difficult topic for students so it needs to be thoroughly taught if students are to be able to use the ideas skilfully. However the evidence from studies about how students learn stereochemical ideas is scant and therefore the thesis will develop a firmer background of students' conceptions about stereochemical ideas and also develop and evaluate a computer-based learning approach to teaching the topic.

3.2. METHODS AND SUPPORTIVE TOOLS/ STRATEGIES EFFECTIVE FOR TEACHING CHEMISTRY

Both learning and teaching theories, constructivism and phenomenography hold that scientific concepts including chemistry are unlikely to be discovered by students on their own, but that rather they must be taught to students (Driver, 1995; Driver et al., 1994; Marton & Booth, 1997). The application of such ideas to the learning and teaching of chemistry has resulted in the development of discipline – specific strategies/tools that facilitate the learning of chemistry.

In summary, student learning of chemistry depends on the way the student is taught and can be promoted by an appropriate (teacher's) intervention, in which the teacher introduces the use of different chemistry-specific methods and tools/strategies aimed to facilitate students' conceptual development when introducing different concepts (such as stereochemistry). The teacher's instruction of chemistry concepts always depends on teacher's pedagogical content knowledge (PCK), and involves the integration of the teaching strategy employed and teacher's knowledge of the subject content by the use of chemistry-specific tools or strategies.

Traditional methods for teaching undergraduate chemistry are dominated by lectures, tutorials (also called discussion sessions) and laboratory based instruction (Committee on Undergraduate Science Education, 1997). To make effective any of these methods teachers combine different strategies. Although, as Committee on Undergraduate Science Education stated, there is no universal best way to teach chemistry, there have been experiences of those involved in teaching undergraduates that succeeded with

student engagement, even in large classes, and they are described as effective.

3.2.1. Lectures

According to Committee on Undergraduate Science Education (1997) evidence from a number of disciplines (physics and chemistry) suggests that oral presentations to large groups of passive students contribute very little to real learning. Despite the limitations of traditional lectures, many universities are forced to offer high-enrolment science courses with lecturing as their only option in teaching these courses. To engage students and enhance their learning in large classes lecturers utilise different practices (e.g. provide notes, use of multimedia, video and audio clips) and strategies such as the use of physical or concrete molecular models (described later together with other tools aimed to promote conceptual understanding). Different practices and strategies differ from one individual teacher to another and they are dependent on the concept being addressed. The Committee (1997) listed hints for student engagement and more effective lecturing, but also suggested that asking questions and chemistry demonstrations may play an important part in guiding students' learning. In questioning, a lecturer's questions should build confidence rather than induce fear and the lecturer should encourage the students to propose several different answers to the question.

(i) Demonstrations

If properly planned and designed, demonstrations can be very effective for illustrating concepts in class. Demonstrations can provoke students to think for themselves and they are especially helpful if they have a surprise, if they challenge an assumption or illustrate abstract concepts or mechanism (Committee on Undergraduate Science Education, 1997). However, demonstrations can result in passive learning without careful attention to engaging students. O'Brien (1990) listed a number of important issues to be considered when planning a demonstration.

3.2.2. Tutorials

According to Committee on Undergraduate Science (1997) tutorials are used in large-enrolment courses to supplement the lectures and are aimed to engage small **group discussion** sessions. Discussion can be instructor-centred or student-centred in which

the instructor mainly guides the discussion towards important points. For many chemistry students, to develop conceptual understanding and to learn problem-solving skills, instructor-centred or focussed discussion was found effective (Committee on Undergraduate Science Education, 1997). Classes in which students participate in focussed discussion force the students to go beyond merely plugging numbers into formulae and memorising terms (see social constructivist view and the Vygotsky's ZPD). Students learn to explain in their own words what they are thinking and doing.

Student-centred discussions are less predictable and more time consuming. To ensure that the key points are covered and to keep the discussion from becoming disorganised or irrelevant these discussions require a teacher's guidance. This strategy may not work for all students, especially those who do not spontaneously engage in a discussion, those unprepared or reluctant to speak.

The strategies that involve discussions must be carefully planned and flexible enough to adjust the character of different classes.

A variety of educational approaches that involve joint intellectual effort by students or students and teachers together is known as collaborative learning (supported by sociocultural constructivism). Cooperative learning, a form of collaborative learning, is an instructional technique in which students work in groups to achieve a common goal, to which they contribute in individually accountable ways.

3.2.3. Chemistry Laboratories

Chemistry laboratories are settings for hands-on experimentation, which, according to the Committee (1997), underlie chemistry knowledge and understanding. They provide students with the opportunities to think about, discuss and solve real problems. However, many authors pointed out that despite the importance of experimentation in chemistry, laboratories fail to convey the excitement of discovery to the majority of students and fail to provide the conceptual understanding to the learners (Committee on Undergraduate Science Education, 1997; Draper, 1998; Johnstone, 1999). The Committee (1997) suggested that laboratory classes should be coincident with the lecture or tutorial and that "developing an effective laboratory requires appropriate space and equipment and extraordinary effort from the department's most creative teachers" (p. 17).

Chemistry laboratories can be designed for cooperative learning, they can be enriched by computer-based applications. However, the use of computers should never completely replace the student's interaction with the natural world. In addition, the Committee (1997) pointed out that there is no substitute for an instructor "circulating among students, answering and asking questions, pointing out subtle details or possible applications, and generally guiding students' learning" (p. 18).

In laboratory classes students should learn to keep a record while doing an experiment. The record should be considered in the laboratory report, which is a part of laboratory classes. Reports may be oral or written. Oral reports motivate students to understand their work well enough to explain it to others, they are time consuming, but they do not give students practice in writing. The formal written report teaches students how to communicate their work in a journal style.

In conclusion and according to the Committee (1997), many benefits of carefully planned laboratory classes can be realised only if the instructional staff is well prepared to teach (they should be masters of the laboratory experiments and on the methods used).

3.2.4. Supportive Tools/Strategies Effective for Teaching Chemistry

As mentioned earlier, the instruction given by any of the traditional teaching methods (lectures, tutorial, laboratories), can be and often is supported by the use of molecular models; analogies; diagrams; concept maps; cooperative group work; multiple teaching models or the use of computers, all with an aim to facilitate students' conceptual development. Because of their importance in teaching stereochemistry, a description and the use of these tools/strategies are given below. Others, such as concept maps (Novak, 1995; Pendley, Bretz & Novak, 1994), although used in both science instruction and evaluation of student learning, were not employed in the studies of the thesis and their description is excluded. Because facilitating learning by the use of computers is the more narrow focus and the overall concern of this thesis, the use of computers as a significant tool in teaching is described later in a separate chapter, Chapter 4.

Barta and Stille (1994) noted that principles involving stereochemistry are among the

first stumbling blocks that students encounter in organic chemistry. Because students' backgrounds, experiences and degrees of intellectual skill development are as varied as the number of students in the classroom, different tools for conceptual development (also called models or methods) may be introduced but the effectiveness of each is dependent upon the individual student (Barta & Stille, 1994; Mezl, 1996; Yamaha 1989a; Yamaha, 1989b; Zoller, 1990). These tools or strategies vary from mathematical approaches and two-dimensional Fisher projection techniques to three-dimensional molecular models or the use of analogies. In addition, multiple teaching strategies have been suggested.

(i) Molecular Models

Ingham and Gilbert (1991) described models as invaluable teaching aids in teaching abstract concepts because the model represents an abstract idea but is itself concrete. According to the authors a model is a simplified representation of a phenomenon that concentrates attention on specific aspects thus facilitating scientific inquiry. By simplifying complex situations, models enable a phenomenon to be studied one aspect at a time and a vocabulary to be developed by which phenomena may be discussed.

Ingham and Gilbert (1991) classified different types of models into scale models, analogue models, mathematical models, theoretical models and archetype models. The authors state that the boundary conditions for inclusion in the category of 'analogue models used in chemistry' are hard to define and that for most chemists 'structural models' are equated to 'analogue models'. Because of the difficulties in defining exact boundaries between different types of models, in this thesis the term model is used for three-dimensional physical or concrete ball and stick representations and these are specifically called molecular models.

Generations of students have constructed concrete ball and stick molecular models in chemistry classes. They are able to investigate models of molecules and their three-dimensional shape by rotating and inverting the model and observing it from different views. Ingham and Gilbert (1991) reported that higher level students, such as honours graduates, science teachers or chemistry degree students, also found molecular models useful in their learning of chemistry because the use of molecular models helped them to grasp certain fairly abstract concepts. However, the study revealed that students are often unclear about the chemical usage of the term 'model', for example considering

various types of chemical formulae to be models. A study by Gabel and Sherwood (1980) revealed that allowing students to manipulate molecular models themselves rather than watch the teacher use them in demonstrations could enhance chemistry achievement. The authors also revealed that manipulation of molecular models should be used over an extensive period, at least one semester, until the students become familiar with them and increasingly as the course continues are able to use them to organise new concepts. Staver and Halsted (1985) reported that the effectiveness of using models during testing depended on the learner's capacity to employ certain reasoning patterns, including sex-related spatial reasoning. They found the use of models during testing more effective for low reasoning males and high reasoning females but less effective for high reasoning males and low reasoning females. Staver and Halsted also suggested that the use of three-dimensional molecular models during instruction on an abstract concept such as molecular geometry, shape and polarity are beneficial because the level of abstraction is reduced.

Laws (1996) suggests the use of models for 'reality' when "that reality is reluctant to cooperate with teachers efforts to educate a class of students" (p. 51). If a model is employed for teaching 'conceptually difficult' phenomena, it is possible that the model used may not communicate the information to the student that is intended by the teacher.

(ii) Analogies

Analogical thinking is very common in everyday life. Whenever a new phenomenon is too strange or complicated for us to deal with directly, we represent whatever part of it we can in terms of more familiar concepts. Analogical thinking is also quite common in science. Throughout the history of science, analogies have played an important role in explanation, insight and discovery (Glynn, Duit & Thiele, 1995). Making analogies involves finding similarities between a new concept and a familiar one in order to make the new concept more understandable. Pressley and McCormick (1995) suggested that analogies can be useful even if students do not possess misconceptions related to the to-be-learned idea, particularly at those times when the material to be learnt is difficult to understand because it is from an unfamiliar or abstract domain. A study by Stavy (1991) described the use of analogies as an effective tool to overcome misconceptions about conservation of matter. To activate and support their correct intuitive knowledge, at first

children were introduced to the concept of conservation of matter with an iodine evaporation task. Then, they were presented with the same scientific concept with the analogous but often misunderstood acetone evaporation task.

For an analogy to mediate effective learning of new content learners must understand the analogy and the limitations of the analogy used, since even the best analogy breaks down at some point and could become a potential source of misconceptions. Pressley and McCormick (1995) suggested that a multiple analogy approach together with the use of explanations that warn of breakdowns might reduce the impact of the shortcomings inherent in analogies and help students to better understand scientific concepts.

In teaching stereochemistry, the analogy of a steering wheel is popular and has been used in some textbooks (McMurry, 1992; Wade, 1991). The utility of hands as asymmetric teaching tools or the use of 'right hand rule' is the most readily available analogy, used for undergraduate students who are just learning stereochemical concepts, but also the graduate students, who already teach, find themselves using their hands for more complex molecules. The success of this method is due to the constant availability of the hands as tools (Barta & Stille, 1994; Beauchamp, 1984).

(iii) Diagrams

In addition to the use of molecular models and analogies, the use of pictorial representations such as diagrams is also common to support verbal or textual representations of chemical concepts in traditional lectures, laboratory classes or textbooks. It is only necessary to open a chemistry textbook to notice the role of coloured, pictorial presentation of the abstract concepts of atoms, molecules or electrons.

A number of different remedial instructions that have been developed to help students with the difficulties involving three-dimensional tasks involve the use of diagrams (Shubbar, 1990; Tuckey, Selvaratnam & Bradley, 1991). Tuckey et al. (1991) reviewed the studies that explored the role of the use of different kinds of diagrams in helping students with difficulties in visualising rotation, such as monochrome or multi-coloured projected diagrams to simulate the effect of motion. While no significant improvement was noted in learning if the diagrams were exposed one at a time, or if the diagrams used were monochrome it has been found that the use of multi-coloured diagrams

brought a significant improvement in student ability to visualise rotation.

(iv) Socially Supported Collaborative Construction of Science Concepts

Theorists and educators believe that socially interactive instruction permits students to experience distributed cognition. This is consistent with Vygotskian theory (Vygotsky, 1978), known as instruction within the zone of proximal development and refers to the instruction that leads children to construct new knowledge in collaboration with others. According to Vygotsky (1978), students conceive much of thinking through interaction with each other as well as interaction with a teacher. When successful, different points of view on the same situation result in the appropriation of one view by another. Ideally, this appropriation process leads to conceptual change.

Johnson and Johnson (1986) concluded that under most conditions groups are more productive than individuals. Kogut (1997) found that cooperative learning of chemistry for first year students is both feasible and desirable. A study by Dougherty (1997) has shown a significant increase in both learning and retention of concepts in general chemistry, when students worked in cooperative groups.

However, social interactive instruction and problem solving may not always be equally beneficial to all students. If one person does most or all of the work other members of the group learn little. A study by Basili and Sanford (1991) revealed that poor leaders prevented effective discussion by rushing through questions and imposing their narrow view on the purpose of the task. Cohen and Ben-Zvi (1992) investigated chemistry high school student achievement in groups by implementing new learning materials and strategies (inquiry questionnaires based on laboratory experiments, teaching aids such as multi-layer transparencies, structured learning materials and learning games). To compare a treatment group with a control group (which used current textbook and conventional learning strategies) Cohen and Ben-Zvi employed pre-test and post-test scores. They reported that group achievement depends both on the complexity of the task and students' abilities. For a relatively easy learning task, the low-ability students benefited more from the group setting than from individual learning, while there were no differences in the achievement of high-ability students. For more difficult learning tasks, high-ability students performed better in group discussion, while the group activity did not give advantages to low-ability students. A more recent comparative study by Banerjee and Vidyapati (1997) investigated the effect of lecture and

cooperative learning strategies on achievement in general chemistry. The study involved 68 first semester undergraduates in a teacher preparation course, divided into two groups (35 students in the lecture class, 33 in the cooperative learning class). Three separate tests on three units were developed and quantitative statistical analysis was applied (the mean scores, standard deviation, t-test and effect size). The authors found similar achievement by the most common method of instruction namely lectures and the 'now so popular' method of cooperative learning. They suggested that cooperative group learning might need to be supplemented by whole group discussion and lectures.

In conclusion, the reviewed literature suggests that the optimal social intervention for instruction in scientific topics should involve participation of all students and the presence of a skilled teacher, who can detect a variety of prior conceptions that students possess and intervene appropriately. An approach which is more likely to facilitate the learning of a group of students with a range of diverse needs, is the approach that involves a combination of different instructional strategies.

(v) Multiple Teaching Approaches

If the philosophy of Lemke and postmodern semiotics constructivism (1994) is applied to chemistry, then chemistry speaks in many different modes of representations or different languages of a scientific concept such as verbal, visual, or mathematical semiotic system. Further, if the role of chemistry education is to teach students about all those different languages, their meanings and their use (Lemke, 2002), then it is more likely that this role can be achieved by teaching in which multiple teaching approaches are employed.

Many authors have suggested that the use of multiple teaching aids can help to improve the understanding of scientific concepts (Lee, Eichinger, Anderson, Berkheimer & Blakeslee, 1993; Pressley & McCormick, 1995). This is in accordance with the dual processing theory, as text and illustration or speech and animation (dual mode presentations) are more likely to stimulate deep or meaningful learning rather than single-mode presentations, such as in traditional instructions with verbal modes only (Hartley, 1994; Mayer & Moreno, 1998; Williamson & Abraham, 1995).

Kleinman, Griffin and Kerner (1987) investigated translation between images and other forms of chemistry knowledge. They selected a list of chemical terms that might be associated with images from standard chemistry texts, and designed a procedure to

determine the specific images that participants associated with these terms. Ten undergraduates, eight graduates and three faculty members were interviewed. The authors identified three levels of abstraction (or categories) in which participants experienced the chemical image with an increasing order in complexity and abstraction: associative, real and model. At the most abstract level of imaginary development the images are no longer in the observable world but are constructs based on abstract models. Kleinman et al. concluded that students may be unable to learn chemistry, and that classroom communication may fail, because they cannot relate to or form the image appropriate to a concept. To help students to form the image appropriate to an abstract concept, traditional teaching should be accompanied with a variety of aids.

Although many teaching strategies have been promoted as being more effective in meaningful learning than traditional expository instruction, their demonstrated success rates on the acquisition of scientific concepts are far from perfect. The study of Noh and Scharmann (1997) revealed evidence of the limited success of pictorial presentation at the molecular level, if presented as an instruction alone. They suggested that such kinds of instruction are effective at improving students' understanding when introducing new or difficult chemistry concepts, if combined with other instructional methods such as traditional expository teaching or cooperative learning. This is in agreement with the dual processing theory of working memory that includes auditory working memory and a visual working memory and advocates better transfer of information if the pictures and words are presented simultaneously (Hartley, 1994; Mayer & Moreno, 1998). A study by Kleinman et al. (1987) also showed that students' communication of chemical concepts can be an effective aid to learning if the student can associate written and spoken symbols with appropriate representational images.

Hartley (1994) suggested that representing information in different forms also has a marked influence on our thinking. The same study reported that the use of pictures without adequate textual or narrative support gave disappointing results, which is similar to findings of Noh and Scharmann (1997) described above. To make effective use of visuals within textual material students need to actively link the information provided by both modalities. Noh and Scharmann (1997) highlighted that active student involvement, in which students interact both with each other and examine the concept independently of each other, plays a key role in achieving conceptual understanding. The study by Basili and Sanford (1991) suggested that conditions for conceptual change

need both active, direct instruction by a knowledgeable and skilful teacher and active participation and cognitive struggle by the students.

In addition, there is a viewpoint that telling stories may play an important role in teaching and learning of science (Solomon, 2000).

Multimedia learning opens up the possibility of integrating multiple teaching aids (to integrate text, diagrams, models, analogies, animations, even stories), a process supported by the dual-processing theory (Hartley, 1994; Mayer & Moreno, 1998). Computer-assisted cooperation between students working on the computer can be used to integrate multiple teaching aids aimed to promote better learning. A more detailed description of learning chemistry using computers follows in the next chapter.

3.3. SUMMARY

The complexity of learning and teaching of chemistry can be more clearly revealed only if the complex nature of chemistry is considered together with the processes of learning and teaching.

The research into the nature of chemistry, in combination with the research into student learning and teaching, has revealed the requirements needed to facilitate the learning of chemistry and has resulted in the development of many methods and supportive tools/strategies for teaching chemistry. The learning and teaching theories considered in the thesis (constructivism, phenomenography) proclaim that science (so chemistry as well) must be taught or introduced to students (Driver, 1995; Marton & Booth, 1997).

In order to facilitate student learning of the mostly abstract concepts of chemistry (represented in micro and symbolic forms), a variety of different tools/strategies have been developed (such as *Molecular models*, *Analogies*, *Diagrams*, *Cooperative grouping strategies* and *Multiple teaching approaches*) and have been used to accompany lectures, laboratory classes or tutorials. Any of the strategies/tools used for conceptual development mentioned above may be a useful intervention in teaching stereochemistry, particularly if combined as multiple teaching approaches. One of the tools for presenting and manipulating information that can cause learner's conceptual development and therefore help in learning and teaching chemistry, which also combines different approaches, is *The use of computers* and this is described in the next chapter.

4. COMPUTER SUPPORTED LEARNING AND TEACHING OF CHEMISTRY

This chapter is a continuum of the previous one in which the focus narrows to the learning and teaching of chemistry in a computer-based environment.

Computers are transforming the ways of doing and thinking about chemistry. They are critical in the design of new drugs, the solution of crystal structures and the development of quantum chemical models of our molecular world. More importantly for this research, computers are starting to transform the ways we learn and teach chemistry. However studies that probe the student learning in chemistry associated with computer use are relatively scant and for that reason this topic is described in this thesis.

The studies described in this thesis relate to the use of software in learning and teaching chemistry, therefore research on such software use will be reviewed in this chapter.

Many different terms associated with the use of commercial software in education can be found in the literature. For example, computer-aided instruction or computer-assisted instruction, CAI (Wainwright, 1989), computer-assisted learning, CAL (Draper, 1998) or computer-based learning, CBL (Tait, 1998; Wills & McNaught, 1993). In the late 1990s terms such as multimedia learning environment, technology enhanced learning environment or information technology (IT) also appear in the literature (Hannafin & Land, 1997; Kirsh 1997; Lawless & Brown, 1997; Tait, 1998). These terms and other acronyms that are appearing in educational literature are intended to highlight the purpose of computer use, as well as the research being done, for example into instruction or learning. In this chapter, which reviews the literature of software use, the terminology preference of the author/s will be respected and the terms used will be those from the original paper.

However, the term CAI is utilised in the studies described in the thesis (Chapters 6-9, that follow), with the assumption that instruction (teaching) and learning by computers are interwoven and cannot be separated from each other (as was described in previous chapters). Furthermore, the outcomes and messages derived from any particular study may be useful to all participants in the computer supported learning and teaching of

chemistry (for example software designers, teachers, students).

The phenomenal growth of the Internet over the last few years presents exciting new opportunities for educators. Tutorials are being offered on the World Wide Web and chemistry papers are being offered for distance learning. However, a study by Benyon, Stone and Woodroffe (1997) argued that the hypermedia capabilities offered by the World Wide Web require careful consideration. The authors argued that the current tools are severely lacking in a number of important respects - particularly with respect to the design of pedagogically sound courseware. Bell, Gladwin and Drury (1998) discussed the advantages of the World Wide Web as a method of supplying software, but also pointed out that one of the difficulties in using it lies in finding high-quality information from the wealth of available Web sites. Science teachers often decide to design their own software to fit their own teaching requirements and learning needs, rather than use the software available on Web sites (Burke, Greenbowe & Windschitl, 1998). This was why the in-house authored stereochemistry tutorial was written in Study Two. Although available just internally for Massey University chemistry course undergraduates, the tutorial was designed for web-based use and therefore web-based learning.

A substantial number of papers addressing computer supported learning and teaching are regularly being published in educational journals. Furthermore, the plethora of the research influenced by and produced as a consequence of computer use in everyday teaching and learning practices, has resulted in a constantly increasing number of journals dedicated only to computer supported learning and teaching. Dobson as a guest editor of a special issue of the prestigious journal *Learning and Instruction*, 9 (1999) declared:

Making a special issue of **Learning and Instruction** that focused on interactive graphical systems, is an indication that computer-based learning has become truly classroom mainstream. The appearance of this collection of articles demonstrates an appetite for reliable results of interdisciplinary research in learning with technology. Educational computing remains centred among research in many fields, and has always been able to take benefit from many disciplines wherever guidance can lead to creative and systematic use of learning technologies. (p. 303)

The interdisciplinary nature of the use of computers in learning and teaching is discussed below.

4.1. PHILOSOPHICAL BACKGROUND OF COMPUTER SUPPORTED LEARNING AND TEACHING

According to Lower (2000) computer supported learning of chemistry fits into the constructivist philosophical view of learning. Computers are also particularly suitable tools for providing learning by guided discovery/scientific discovery. Some aspects of these psychological and philosophical views are described below.

4.1.1. Learning by Computers: A Constructivist-Based Approach

If well designed, CAI is a type of instruction that promises to provide student-centred or student-controlled learning (Goforth, 1994; Lower, 2000; Schaefermeyer, 1990). Consequently, such instruction should enable the learner to construct knowledge. This is the most important assertion that the theory or philosophy of constructivism makes about student learning (Cunningham, 1991; Driver, 1995; Driver et al., 1994; Gruender, 1996; Savery & Duffy, 1995). Lower (2000) mentioned the student's freedom of being able to give the wrong answer 'without anyone knowing', while Schaefermeyer (1990) and Goforth (1994) talked about the advantages of being able to progress through the task at his/her own pace and repeat the same task as many times as required. Most CAI employs the Socratic method of asking a series of questions, which lead the students to discover the answers for themselves (Lower, 2000). According to Lower, being questioned instead of being 'told', is a methodology that encourages active engagement by students in decision making that facilitates the learning process. Furthermore, much CAI also involves animations and simulations aimed to improve visualisation, which can promote constructivist learning by discovery or scientific discovery (Van Joolingen & De Jong, 1997). This form of constructivist learning was described in Chapter 2.

4.1.2. Matching the Software Development with Educational Theory

Much of the research on software development is based upon a psychology-based dual processing theory (described in Chapter 2). Knowledge of how learners mentally integrate information presented, using multimedia, informed and improved the design

and implementation of multimedia materials. According to the dual – processing theory, both pictures and words activate learners' conceptions (mental representations) to be formed also in both imaginal and verbal codes (Dobson, 1999; Hartley, 1994; Williamson & Abraham, 1995).

Apart from taking into account the psychological assumptions of multimedia learning, two other aspects seem to play an important role in software implementation in teaching and learning. The first one takes into account the philosophical assumptions of content-related learning and teaching theories current in education, the second one arises from the theories born out of the research in software development. The latter is the product of the former and the incredibly fast growth and development of knowledge about information technology.

Research into software development has shown that branched software design, which provides the students with adaptive feedback (Goforth, 1994; Mory, 1994; Whyte, Karolick, Nielsen, Elder & Hawley, 1995), is to be preferred over linear designs (Biemans & Simons, 1996; Goforth, 1994; Schaefermeyer, 1990). Schaefermeyer (1990) described branching as “the one most prominent element that makes the computer a valuable tool for individualising instruction” (p. 11), while Goforth (1994) described how branching enables ‘learner controlled destination’ and not the ‘program controlled destination’.

Nonlinear or branching software design opened the possibility of employing adaptive feedback. In adaptive feedback the next destination is not program predetermined, but depends on the student's answer and quite often prescribes subsequent activities. Mory (1994) described the computer as a dynamic delivery system that, when used for instruction, can allow for interactive strategies and adaptations according to various learner and task characteristics. Whyte et al. (1995) also considered feedback as a fundamental component of well-designed computer assisted instruction. Goforth (1994) elaborates this computer role as a tutor role, in which the ‘intelligent’ tutoring system “attempts to understand the learner as a tutor does” (p. 3). Chung and Reigeluth (1992) described that the use of intelligent computer-based tutoring systems requires more participation of the learner in the learning process. This discussion is in line with learning and teaching theories that support student-determined learning.

However, in developing learner controlled software, it is often not easy to match instructional systems design and learning theory. Rodrigues (1998) studied the

interaction of software designers with an educational researcher during the development of nonlinear chemistry software. According to Rodrigues (1998), a nonlinear design of software allows the student to construct knowledge. However, she described differences in understanding the on-screen instructions from the constructivist point of view (her own as a researcher) and from the point of view of the software designers, thus indicating possible difficulties that could arise in learner-software interaction. Computer software offers the learner adequate information for conceptual change and allows the learner to construct knowledge if the instruction given matches the learner's needs.

De Jong and Van Joolingen (1998) reviewed scientific discovery learning by computer simulations. Their general conclusion from the studies they analysed was that there is no clear and unequivocal outcome in favour of simulations. A possible reason why simulation-based learning has not been shown to improve learning results can be found in the intrinsic problems that learners may have with discovery learning. These authors identified a number of characteristic problems that learners encounter in discovery learning, such as hypothesis generation, design of experiments or interpretation of data of discovery learning. As a solution De Jong and Van Joolingen suggested combining simulations with additional support, such as instructional support. Three individual instructional measures have been found to hold promise of positively influencing learning outcomes:

1. Providing learners with direct access to domain knowledge or domain information, so that they can ask for a definition of a concept for instance. This instructional measure was described effective as long as the information is presented concurrently with the simulation, and is thus available at the appropriate moment.
2. Providing learners with assignments (or questions, exercises or games). These instructional measures encourage and actively engage learners in making decisions, leading them to discover answers for themselves.
3. Providing learners with an environment that includes progression, with an increased complexity or degree of elaboration.

Other individual measures such as hypothesis support, experimentation hints, monitoring tools, and prediction support were also discussed but the evidence was not found to be substantial enough to warrant general conclusions (De Jong & Van

Joolingen, 1998). A number of studies suggest that structuring the environment by providing the student with a sequence of experimental steps can lead to more effective learning. All different kinds of instructional measures that can be given to direct students in a certain way can be described as guided discovery.

De Jong and Van Joolingen (1998) highlighted the importance of 'intuitive' or 'deep' knowledge for scientific discovery and the advantage of simulations when the instructional goal is the mastery of skills, but questioned whether the associated conceptual knowledge is necessarily learned too.

(i) Computer-Assisted Cooperation

As described in the previous chapter, many studies have suggested that the teaching approach that involves multiple teaching aids can improve student understanding of scientific concepts (Lee et al., 1993; Pressley & McCormick, 1995). Computer-assisted cooperation is an example in which multiple teaching aids are integrated in order to promote better learning (Johnson & Johnson, 1986; Lynch & Clarke, 1997; Ruberg, Moore & Taylor, 1996).

According to Johnson and Johnson (1986) tasks presented by computers might be structured individualistically, competitively or cooperatively. They described the strengths of computer-assisted cooperative learning and indicated that the effectiveness of cooperation increases as the task becomes more difficult, ambiguous, conceptual or in need of divergent perspectives. Ruberg's et al. (1996) qualitative study explored student participation, interaction and regulation in a computer-mediated communication environment. Thirteen students (19-20 years of age), all biology majors, participated in the plant science laboratory experimental class. The authors found that on-line interaction is an alternative that facilitates student participation, getting students who never spoke in face-to-face settings actively engaged in the on-line discussion. They highlighted the importance of students constructing meaning by taking time to put their newly learned concepts into their own words. They also pointed out that the success of computer mediated tasks depends on the selection and structure of the task and the teacher's role in providing links to other pre-existing and upcoming learning activities. The discussion by Ruberg et al. (1996) is in line with Vygotsky's sociocultural constructivism. Lynch and Clarke (1997) found that computers could promote and enhance students' verbal communication of scientific phenomena and hence

understandings in ways that could not be achieved on paper.

4.2. COMPUTER SUPPORTED LEARNING AND TEACHING EVALUATION

The increasing presence of computers in our everyday learning and teaching practice opened up the need for research to evaluate the kinds of learning and teaching that the computer programs provide.

According to Dobson (1999) computer-based learning and teaching is interdisciplinary research itself. Therefore, multiple aspects should be considered in any of the aspects of the research connected with computer-based learning and teaching, and so should be considered for the evaluation process.

New trends in evaluation of computer supported learning evolved from:

- the evolution of learning and teaching theories,
- technology development and its application in education,
- the research that focussed on the changes in paradigm (from purely quantitative towards qualitative as well) that took place in the evaluation of learning in general.

Much of the discussion that can be found in the literature indicates that the inputs given above are interwoven and contribute together in understanding of how evaluation of the computer-based learning developed. Wills and McNaught (1993) highlighted, for example, the importance of the constructivist views in computer-based learning and argued that a quantitative evaluation is not sufficient without qualitative support.

The change in evaluation of learning with technology from 1960s to 1990s followed the change and the development of the computer-based applications in education (Gunn, 1998). According to Gunn the change in evaluation learning with technology can be described as a shift from isolation to integration as the interdependence of content, context and individual characteristics became increasingly recognised.

According to Gunn, computer-assisted instruction, program-controlled learning and the use of branching programs were the types of computer-based applications in the 1960s. Evaluation typically meant attempting to isolate the effects of a single resource and the creation of 'clean' experimental situations in order to reveal the objective truth about

the impact of particular intervention. The experimental studies were controlled and based on a behaviourist, measurement oriented paradigm that regarded learning as independent of subject or context and resulted in scores and outcomes with no relevance attached to process or context. This paradigm, articulated in the 1930s by Tyler and Skinner, was based on stimulus - response related assumptions about learning.

In the 1970s tutorial programs and simulations also appeared as computer-based applications, in which the importance of culture (social, political and economic factors) emerged. The research that was carried out involved predominantly an experimental evaluation. New evaluation methods included interviews, questionnaires, profiles, think aloud protocols and observation, and resulted in descriptive findings. The findings identified the contribution of many factors that were involved in achieving effective learning outcomes, for example teaching and learning styles, prior knowledge, motivation, classroom culture and method of assessment. The development of grounded theory enabled researchers to make generalisations from the initially case specific findings.

As Gunn described, when microworlds, complex simulations, intelligent tutoring and generative programs appeared in the 1980s, the need for responsive/evaluative methods became clear. Still, academic credibility for qualitative methods was far away. The experimental methods failed to produce sufficient details for evaluators and designers' purposes in formative and summative studies. For this reason, naturalistic methods based on the interpretive and critical paradigms became increasingly popular. In addition, the usability studies that evolved took over the learning evaluation and the design guidelines and standards. Findings were given in the form of formative evaluation results and the generalisations of the results on learning issues continue. Various forms of user testing that were used gave important inputs to development. Reported case and situation specific factors that were identified, showed a shift away from large experimental studies.

Online courses, user generated resources, full multimedia simulations and tutorials are types of CAL that have appeared in the 1990s. The evaluation includes integrative response studies (that for example emphasise the importance of context) that are conducted in authentic contexts using mixed methods and multiple data sources. Methods used accommodate different situations, such as where teachers and students never meet face to face. Evaluation has been accepted as an important ongoing aspect of

program and course improvement. Studies involve qualitative and quantitative measures, as appropriate, and findings are given in a loop representing the ongoing process of plan - implement - evaluate - improve.

Wills and McNaught (1993) described the nature of research in computer education in the eighties and early nineties. According to these authors, the majority of the research in computer education at that time addressed educational software development and the implementation of teaching innovations, as well as authoring languages and teacher training issues, with only about 20% dedicated to the impact of computers on the learning process. The studies were classified into the following categories of evaluation: Quantitative data; Student and Staff Attitudes and Perceptions to use of Computers for Learning; Formative Evaluation for Instructional Design of CBL Packages; The Effectiveness of CBL in Comparison to the Effectiveness of Conventional Teaching; Providing Evidence about Whether CBL Enables Students to Learn Effectively; and Providing Information from which Curriculum Changes can be Made (Wills & McNaught, 1993). The methodology employed in most of these studies was based upon the experimental - control group design and/or pre and post testing, in which measuring a difference in student achievement between two selected groups was used as a measure of effectiveness of computer-based task that was implemented. The authors pointed out that numerous studies have attempted to compare computer-based learning delivery with traditional delivery and reported little 'significant' difference in learning outcomes but overwhelming evidence of attitudinal difference. Hattie (1999) comments on studies that report the measuring effect-size of school achievement:

The missing step is that comparison should NOT be to zero point; we must not compare having computers to not having computers, we must not compare ourselves as teachers to not having us, but we compare innovations to other innovations.(Measuring the effects of schooling, para. 10)

A study by Marriott and Long (1993) attempted to answer the question: Does instructional software designed to engage and interact with students' existing knowledge improve learning achievement? They also employed an experimental - control group design and used pre and post testing to determine the student achievement difference of two groups in five selected learning concepts from an introductory university statistics course. The analysis suggested that there was no significant difference between the groups. Marriott and Long argued that the interaction embodied in these technologies may not be the type of interaction that promotes learning, and that

the term interaction refers rather to the manipulation of screen objects by the use of mouse or pressing the button to go to the next screen.

Recognising the presence of a diversity of modes of delivery such as tutorials, simulations etc. and the diversity of its context, computer-based learning cannot be evaluated in an absolute sense, but only on the effectiveness of a particular piece of application (Wills & McNaught, 1993). This is in agreement with Draper (1998) who argued that there is no generalisation about what features of technology or software type makes a piece of CAL successful. On the contrary, according to Draper, the most definite successes seem to come from a close fit between a piece of courseware and its situation of use that is specific to that niche.

In the analysis of the studies on learner control in computer-based instruction Reeves (1993) labelled these studies “pseudoscience” as these studies “failed to live up to the theoretical, definitional, methodological and analytical guidelines of the positivist, quantitative paradigm they purport to follow” (p. 39). Reeves emphasised the growing acceptance of the in-depth, qualitative, interpretivist paradigm in educational research and suggested that qualitative research should precede any quantitative inquiry.

New attempts to evaluate computer-based learning are still in the early developmental stage. However, there are studies in the 1990s in which, in order to get insights in terms of computer-based learning, new attempts employed the use of qualitative analytical methods. Qualitative approaches provided the data to inform decisions about whether or not the implementing software matches the needs of those (students) who use it (Roth, Woszczyna & Smith, 1996; Wright, Pavlinic, Buckley & Edwards, 2000). Qualitative studies in physics by Roth (1995) and Roth et al. (1996) have provided useful insights into the use of interactive physics software in the high school setting. In both studies, four student groups carrying out tasks were videotaped, all conversation transcribed and all verbal and nonverbal data were analysed. The analytic methodology employed was informed by interpretive approaches to understanding everyday work practices, human-machine interaction and conversational analysis. Roth et al. recognised the importance of the computer in facilitating student conversation, but concluded that “... while computer environments have some potential as learning tools, they also limit interactions in significant ways, rendering them less than ideal for everyday classroom use.” (p. 995)

In conclusion, if, according to Marton (1999), the use of informational technology

promotes new kinds of learning, then the evaluation should not be based on the traditional paradigms.

The development of the learning and teaching theories that are regarded as valid today and the rapid development of computer technology influenced the development of computer-based applications and the nature of research connected with it. Evaluation of learning using computers shifted over time from the predominantly quantitative to the increasing implementation of qualitative research methodology (DiSessa, 1987; Gunn, 1998).

This section is particularly important for the research employed in this thesis. First, it informs about the on-going trend that takes place in the research on evaluation of computer-based learning; second it justifies that the methods employed in the studies of the thesis follow the same trend, aimed to reveal as much as possible about computer-based learning, in this case, of chemistry.

4.3. COMPUTER USE IN CHEMISTRY

According to Lagowski (1998) chemical education is one of the most attractive areas for utilising computers in teaching and learning. The reasons given below relate to the intrinsic nature of chemistry, as described earlier in Chapter 3:

- Chemistry is grounded in a highly abstract model of microscopic electrons, atoms and molecules.
- Computers can provide animations of the microscopic world and other illustrations to help the novice learner in understanding scientifically correct visual models for the microscopic nature of chemistry. Computer animations which manipulate images of molecular structure can be used as a replacement for static pictures or diagrams and help in the development of student understanding of particle nature of matter (Williamson & Abraham, 1995) or in the development of student visualisation and special ability (Shubbar, 1990; Tuckey & Selvaratnam, 1993; Tuckey et al., 1991).
- In common with the other sciences the computer offers a means of providing simulated experiments to replace or augment the laboratory experience.
- Chemistry is an experimental science. Laboratory classes offer students the

opportunity to experience the macroscopic nature of chemistry. Nakhleh and Krajcik (1993) explored the effectiveness of computer use on laboratory tasks in chemistry.

- Computer offers the possibility of tailoring tutorial instruction to the individual. This target is particularly attractive as class sizes increase as a result of budget trimming.

The selected examples from the literature indicate the type of the research that had been done on the use of computer applications in chemical education, as well as the results obtained from that research.

The study by Williamson and Abraham (1995) explored the effect of computer animations depicting the particle nature of matter on college students' mental models of chemical phenomena. The study consisted of a quasi-experimental, post-test control group design, in which the one lecture session was randomly assigned to the experimental group, whereas the other comprised the control group. Students viewed the animation sequences and answered worksheet questions that focussed on the critical aspects of the sequence. The authors found that lecture animations and lecture/computer lab animations significantly increased the conceptual understanding of the phenomena (effect sizes of about 0.5 were found), by prompting the formation of dynamic mental models of the phenomena. The animation provided a more scientifically correct visual model for submicroscopic processes not easily visualised. Williamson and Abraham argued that the use of static pictures (visuals, diagrams) fail to provide adequate understanding of the phenomena or no mental model of particle nature of matter at all, leaving macroscopic views of the phenomena only. However, the authors reported that there was no subsequent gain when the students were given access to the animations in a computer lab, and there was no significant increase in overall course achievement.

The study by Eggert, Middlecamp and Jacob (1992) reported the findings on the 'intelligent tutoring system', CHEMPROF, that was developed to help students to write a chemical formula when given a name and name a compound from a given formula. In 1991, CHEMPROF was used with a lecture section of 135 first semester general chemistry students of the University of Wisconsin-Madison. Although optional, students were offered up to 100 extra credit points for successfully completing the exercises and most students took the opportunity to earn full points. The responses to

questionnaires at the end of semester revealed a positive student response to the computer tutorials. Furthermore, in a special test, designed to evaluate the skills taught by the tutorials, the students demonstrated an improvement in academic performance in most areas. However, overall course performance was not reported and the authors commented that the program was not being used by students in the manner intended by its authors. Rather than use the tutorial aspect of the program, “students concentrated their efforts on passing the ‘quiz’ that could earn them their extra credit points.” (p. 675).

A study by Yalcinalp, Geban and Ozkan (1995) investigated the effect of CAI, when used as a supplement to classroom instruction in teaching the mole concept. The study, which involved 101 high school students (two classes of the general science course) and the use of pre-test and post-test control group design, showed a statistically significant improvement (of less than one standard deviation) in performance on a special test developed by the researchers. A similar type of study by Wainwright (1989) involved 100 students in two treatment groups, experimental and control, and the post-test only control group design. The study examined the application of CAI to the teaching of nomenclature and chemical equations and showed that the control group using worksheets scored significantly higher than the CAI group.

Not much qualitative research has been done investigating the effectiveness of CAI in chemistry. Particularly, the reports of the research at university level are missing. Nakhleh and Krajcik (1993) studied 15 secondary students on tasks involving pH titrations with or without computer interfaces in a regular first-year chemistry class. They employed initial and final semi-structured interviews, and used concept maps and scores. The authors pointed out that the computer-based task could be used to focus students’ attention on particular aspects of task, such as the form of the pH curve in a pH titration.

Most of research that reported on the effectiveness of CAI in chemistry, other than the studies mentioned above, falls into the similar type of research. Also, the results obtained were mostly optimistic with respect to students’ responses to CAI instruction, but only moderate with respect to learning outcomes as products of CAI instruction. This is in agreement with a general trend of the effectiveness of CAI reported in Fletcher-Flinn and Gravatt’s (1995) meta-analysis study.

In conclusion, the literature that reported on computer supported learning and teaching,

evaluation of such learning and teaching and the type of research and outcomes obtained in computer supported learning and teaching of chemistry, led to the research problem and the research questions for the research described in the thesis, which is described in the next section.

4.4. RESEARCH PROBLEM AND RESEARCH QUESTIONS

Computers have become a constituent of our daily life. It is necessary to ensure that in education the promises the computers are able to offer are achieved.

Implementation of constructivist-based learning and teaching in regular science classrooms has resulted in limited success (Driver et al., 1994; Fraser, 1998). However, according to the constructivist philosophy, the use of computers in chemistry, in which the learner-centred construction of knowledge is promoted by providing the students with well designed teacher-structured instruction, opens up the opportunity to prove the success of this learning and teaching theory (Lower, 2000). From the phenomenographical point of view, computers can provide the learners with different perspectives for viewing phenomena, and by widening the range of the learner's experiences, can promote learning.

In chemistry the use of computers is particularly suitable because it can address different aspects that have been identified as causing difficulties in learning chemistry, but also computers can integrate multiple teaching aids when introducing chemical phenomena.

Computer supported learning and teaching in chemistry has, to date, not shown the 'perfect' match of promises and outcomes. The problem probably lies in the often-identified lack of integration of different, but equally important, features that define computer supported learning and teaching. For example Draper (1998) stated that many developments of computer-assisted learning, past and present, have been technology driven and failed in their educational benefits. Something good in one application is not necessarily as good in another. According to Draper there is no recipe for making computer-based application good in achieving educational aims independent of the educational problem. Judging the cases of different computer-based applications and in order to improve learning using these applications, the author suggested the approach

called '*niche based success*', in which CAI should combine:

1. an identification of a real pedagogical problem;
2. a pedagogic theory of how the educational intervention is a solution to the pedagogic problem;
3. good CAI design;
4. skilled administrator of the teaching and learning using the technology;
5. evaluation and demonstration of the resulting learning gains.

Furthermore, related to the points listed above, it has been argued that possible reasons for the mismatch between the promises and the learning outcomes in the computer-based learning environment could be due to the prevalent quantitative evaluation employed. An approach, in which learning in a computer environment was compared to the traditional forms of learning, in which no computers were used at all, was mostly used in research. Such approach was identified as inappropriate, as in a technology enhanced environment, new kinds of learning that might take place are hardly addressed by the traditional methods of evaluation. Because the computer-based learning and teaching involves sensual and visual experiences and interactive learning of diverse kinds, it was suggested that qualitative evaluation could provide more in-depth insights into, and should be used in evaluating, such kinds of learning.

When the computer-based learning of chemistry is considered, the literature suggests that the use of CAI in chemistry is more the result of the enthusiasm of teachers for computer-based learning than of established strong positive learning gains (Laws, 1996; Pankuch, 1998). Some studies involving CAI in chemistry have shown statistically significant gains in student performance and attitude towards chemistry (Eggert et al., 1992; Wainwright, 1989; Williamson & Abraham, 1995; Yalcinalp et al, 1995).

However, to get insights into student use of computers in chemistry, more qualitative research is needed, particularly at university level.

At the time the research of this thesis began computer-aided instructions were being used in first-year chemistry courses at Massey University. In the middle of the year before work on this thesis started (in 1996), students studying first year chemistry at Massey University were surveyed on their opinions of computer-aided instruction in the course. A small proportion of the 400 students (about 10%) were very enthusiastic, but

the majority was either ambivalent, or negative. This preliminary survey followed a period of rapid escalation of the use of CAI in the course with students being asked to use modelling programs and simulated experiments as well as computer-based tutorials.

The survey results were out of line with student opinion about the other components of the course. In the survey, the lecture programs and the laboratories, received much more positive support. These surprising survey results aroused interest in finding out the reasons for such poor student feedback on the use of such a promising educational tool.

In addition to the survey results, the problem of the mismatch of the promises and the outcomes in computer-based learning of chemistry reported in the literature, initiated the research described in this thesis.

It started by exploring the situation present during the first-year undergraduate chemistry course at Massey University in 1997, by investigating the student use of different chemistry software in the course (Study One). The insights obtained from Study One initiated further directions of the research that followed, from Study Two to Study Four.

During the time the researcher spent in the Chemistry department at Massey University doing the research that is the subject of this thesis, further significant developments were made in the use of information and communication technologies.

It is not only at Massey University that computer aided instruction in chemistry is being discussed and implemented in chemistry education. Rather, the Chemistry department at Massey University mirrored a trend present at many universities worldwide (Lagowski, 1998). Laws (1996) believed that a substantial investment of time and money in the development of the use of computers in undergraduate science education “would pay dividends” (p. 44).

The concern of the research undertaken was to find out critical features influencing the effectiveness of computer-based learning in chemistry and to find some of the answers to the question of how the learning and teaching of chemistry by the use of computers can be successfully achieved. For that reason student interaction with both commercial and in-house authored CAI tasks was explored. Of many views of what interaction means, some relevant to the studies described in this thesis are selected. Rafaeli and Sudweeks (1997) described interactivity as a process-related, variable characteristic of communication settings with engagement as one of postulated outcome. According to

Rafaeli and Sudweeks (1997), interactivity is associated with the attitudinal dimensions of acceptance and satisfaction, but is also related to performance quality, motivation, sense of fun, cognition, learning openness, frankness and sociability.

Barker (1994) described that interactivity in learning is “a necessary and fundamental mechanism for knowledge acquisition and the development of both cognitive and physical skills” (quoted in Sims (1997), Introduction, para. 1). According to Sims (1997), interactivity involves an activity between a learner and a computer-based application. Sims (1997) quoted Jonassen (1988) who described:

Generally, the quality of the interaction in microcomputer courseware is a function of the nature of the learner’s response and the computer feedback. If the response is consistent with the learner’s information processing needs, then it is meaningful. (Why Interactivity, para. 1)

Sims reported five levels of interactivity, identified by Jonassen, which focussed on the user’s involvement with the application and the subsequent effect on learning, i.e. whether surface or deep learning would occur (modality of the learner’s response, the nature of the task, the level of processing, the type of programme and the level of intelligence in design).

Finally, Sims (1997) recalled a detailed taxonomy of interactivity, introduced by Schwier and Misanchuk (1993), which is based on three dimensions: **Levels** (*reactive* which involves response to presented stimuli, *proactive* which involves learner construction and generative activity and *mutual* which involves mutual adaptation of both a learner and a system); **Functions** (*confirmation* refers to verification of learning, *pacing* refers to learner control, *navigation* refers to instructional control, *inquiry* refers to learner interrogation and performance support and *elaboration* refers to knowledge construction); and **Transactions** (keyboard, touch screen, mouse, voice).

The term interaction, used in the research questions below, refers to diverse ways of the participants’ engagements with chemistry CAI tasks. Both cognitive and affective responses resulted from the student-task engagement and included dimensions described by Sims (1997) but originated from Schwier and Misanchuk (1993), and often in combination with one another. While student – chemistry content interaction (the learner’s mental engagement or involvement with the subject material was described as most likely the critical factor of learning effectiveness) may be defined by the function elaboration, student – task design interaction involves many functions (e.g. pacing,

navigation, inquiry, confirmation feedback). The manipulation of screen objects by the use of mouse may be defined as transaction. In cases where student engagement involved groups, the interactions between learners contributed as well (Wagner, 1998).

The main Research Questions are:

1. How do students interact with different kinds of commercially available software, used in a first-year undergraduate chemistry course? (Study One)
2. How do students interact with an in-house authored computer-based tutorial of chemical concept – centred design? (Study Two)
3. What relevant conceptual knowledge and approach to learning do students bring to the computer-based tutorial? (Study Three)
4. How do students interact with an in-house authored, chemical concept - centred computer-based tutorial, amended to take account of student prior knowledge and approach to learning? (Study Four)

To address these questions four studies were carried out and these are reported in chapters 6 to 9 respectively. The four studies described in this thesis were:

Study One - Student Use of Commercial Software in a First Year Chemistry Course. This study responded to Research question 1 and explored student interaction with commercially available computer-based tasks used by first year chemistry undergraduates at Massey University in 1997 (Chapter 6).

Study Two – Student Use of the In-House Developed Stereochemistry Tutorial. This study involved two stages. In the first stage a computer-based tutorial covering stereochemistry was authored to take account of the results of Study One. In response to Research Question 2, in the second stage of the study, student interaction with the tutorial was explored in 1998 (Chapter 7).

Study Three – Students’ Conceptions Underpinning Their Understanding of Stereochemistry. In this study, addressing Research Question 3, the ways in which first year undergraduates understand chemical concepts and approach understanding of the concepts relevant to the topic addressed in the in-house authored computer-based tutorial in Study Two were explored in 1999 (Study Three).

Study Four – Students’ Responses to the Amended Stereochemistry Tutorial. This study also involved two stages. In the first stage the findings of both Study Two and

Study Three were taken into account in amendments made to the computer-based stereochemistry tutorial. In the second stage, addressing Research Question 4, student interaction with the amended tutorial was studied in 2000.

The four main research questions were developed in the relevant studies, identifying specific subquestions (with student – software interaction being more specific). The developed, structured and elaborated research questions are introduced in the appropriate chapter.

It was believed that the insights gained from the research will be useful in:

- improving student learning,
- improving the use of computers,
- helping teachers who are deciding whether to implement already designed programs or author programs of their own.

However, prior to the studies, the methods employed to answer the research questions are described in the chapter that follows, Chapter 5.

5. METHODOLOGY

This chapter introduces and justifies the methodology used in the studies described in this thesis. The chapter includes the rationale for a qualitative approach that has been employed, the research design (including sampling, data collection and data analysis procedures), questions related to ethical issues and comment on the limitations of the studies.

5.1. RATIONALE FOR A QUALITATIVE APPROACH

The main concern of the research described in this thesis was identifying critical features influencing the effectiveness of computer-based learning in chemistry (see previous Chapter 4, section 4. 4.). Sections 4.3. and 4.4. of Chapter 4 already indicated that the qualitative approach would be more suitable for exploring the understandings, meanings and experiences from the student perspective proposed by the main research questions.

Unlike quantitative methods that use, for example, questionnaires, social surveys or structured interviews, and carry out large-scale comparative analyses, qualitative techniques involve more open-ended, ‘free response’ questions based on informal, loosely structured interviews or diaries. They are fairly time-consuming and often used in smaller-scale case study-based research concerned with subjective experience (Denzin & Lincoln, 1994; Griffin, 1985).

The relevance of the importance of qualitative knowledge in understanding chemistry can be nicely linked to the explanation in which DiSessa (1987) addressed the use of equations in science. DiSessa pointed out how equations might symbolise the understanding of a law or principle, but only play a small role in an expert’s knowledge (pp. 346-347):

... One must have the knowledge to interpret phenomena in such a way as to ‘see’ those constructs in the world; one must know the qualitative relationship among those constructs in order to plan and carry out a solution (qualitative controls quantitative); one must be able to recognise pattern in the solution that signal an occasion for apt application of one to another of those relations. ...The more we understand about qualitative knowledge, the more we understand how much has been left out of textbooks of the past and how much is hidden even from the expert’s own conscious view of the field.

According to Merriam (1998) many writers trace the philosophical roots of qualitative research to phenomenology and symbolic interaction (while quantitative research is most commonly linked to positivism). Others draw upon constructivism, postpositivism and critical social science to delineate a view of qualitative research. As discussed in Chapter 4 computer-based learning has a philosophical background in the constructivist theory of learning and teaching (Lower, 2000). If both qualitative research and learning by computers trace their philosophical roots to constructivism, then qualitative approach would be an appropriate approach in exploring the learning and teaching using computers. Merriam highlighted that “qualitative researchers are interested in understanding the meaning people have constructed, that is, how they make sense of their world and the experiences they have in the world” (p. 6). A rich description, which characterises the end product of qualitative research (Merriam, 1998, p. 25), might be an approach which reveals the essence of kinds of learning in computer-based environments, and in ways as experienced by the learners themselves. It is more about discerning of qualitative knowledge of computer-based learning, or what describes this type of learning, rather than employing quantitative measurements by comparing this kind of learning to the traditional kinds of learning.

Research development in multimedia education has shown clear evidence of the importance of qualitative research in this area (Laurillard, 1997). For example there is an increased contribution of articles that explore multimedia education using qualitative methods (Roth, 1995, Roth et al. 1996, Wright et al., 2000). Particularly at a time when a plethora of new software is appearing at an alarming rate (for instance, most of new edited chemistry textbooks are completed with a supplementary CD ROM), the most promising way to get insights into the usefulness of new technologies in teaching and hence learning is to use qualitative research methods.

To discern the complexity of the learning, understanding or knowing that takes place during the student – chemistry software interaction in the studies described in the thesis, a qualitative approach involved the use of natural protocols i.e. observing, video and/or audio recording of students’ actions and conversations while performing the task and interviewing in which students described their experiences. Although slightly different, this is in accordance with Merriam (1998, p. 128) who described that in qualitative research the three basic ways to collect data have traditionally been through interviews,

observations and examinations of documents.

Describing the process of qualitative data analysis Merriam (1998) pointed out that the process is highly intuitive and that a researcher cannot always explain where an insight (that might be a finding) came from or how relationships among data were detected. Merriam (1998) indicated that the different data analysis strategies are options that have worked for those who used and described them and emphasised how the real learning of qualitative data analysis takes place in the doing of the analysis by the investigator.

In the studies described in this thesis, diverse personal experiences of relationship of the researcher to participants were involved (Denzin & Lincoln, 1994). These varied from no formal participation while being a natural observer during the task performance (using the videotape recorder to capture the student - task experience in Study One, Study Two and Study Four), to participation when interviewing the students (all studies).

5.1.1. Triangulation

To address the main research questions, a diverse range of methods of collecting and analysing empirical materials was used. Denzin and Lincoln (1994) suggested that different methods, in combination with one another, can be employed in qualitative research. The use of such integrative methodological approaches is frequent and known as triangulation. The term triangulation has many meanings and usages. As Fielding and Fielding (1986) or Merriam (1998) described, triangulation involves the use of multiple sources of data, and also the use of multiple investigators or multiple methods to confirm the emerging findings. This explanation followed Denzin's (1970) formulation of 'data triangulation', 'investigator triangulation' and 'theoretical and methodological triangulation'. In Denzin's formulation, each of the main types has a set of sub-types. For example data triangulation may include time triangulation, exploring influences by longitudinal design; space triangulation, taking the form of comparative research or person triangulation. In investigator triangulation, more than one person examines the same situation. In theory triangulation, situations are examined from the perspective of different theories. Methodological triangulation has two variants, 'within-method', where the same method is used on different occasions and 'between-method', where different methods are applied to the same subject in explicit relation to each other.

The broad idea in the conventional approach to triangulation is that if diverse kinds of data support the same conclusion, confidence in the conclusions is increased.

(i) Triangulation – Combination of Qualitative and Quantitative Methods

The combining of qualitative and quantitative methods is almost by definition an issue of across-method triangulation (Fielding & Schreier, 2001) or ‘between-method’ triangulation (Denzin, 1970). According to Mayring (2001) the two paradigms stand to gain by no longer ignoring each other and the combination of qualitative and quantitative methods has become almost a commonplace in methodology textbooks.

Kelle (2001) distinguishes three meanings or models of triangulation for conceptualising the combination of qualitative and quantitative methods. These are: (1) triangulation as the mutual validation of results obtained on the basis of different methods (the validity model), (2) triangulation as a means toward obtaining a larger, more complete picture of the phenomenon under study (the complementarity model), and (3) triangulation in its original trigonometrical sense, indicating that a combination of methods is necessary in order to gain any (not necessarily a fuller) picture of the relevant phenomenon (the trigonometry model). These three models are in turn brought to bear upon the potential relationships between the results yielded by qualitative and quantitative methods employed in the same study.

Kelle’s definition (1) for triangulation was recognised earlier by Hammersley and Atkinson (1983), who described that what is involved in triangulation is not the combination of different kinds of data per se, but rather an attempt to relate different sorts of data in such a way as to counteract various possible threats to the validity of (their) analysis.

Triangulation was employed in the research described in this thesis. It involved a combination of methods or integrative methodological approaches (Denzin & Lincoln, 1994). For example stimulated recall interviewing and observational techniques were employed in Studies One, Two and Four. In addition in Study One document analysis was also employed. Therefore all three basic ways to collect data as described by Merriam (1998) were employed. In Study Three phenomenography was supported with document analysis. All studies were supported by the bibliographical collection. The summary of the triangulation based upon the combination of different techniques as

involved in the research and across different studies is shown in Table 5.1.

A number of data sources were also combined. For example in stimulated recall interviewing, semi-structured interviews were combined with tape observing and student laboratory reports (Study One) or researcher generated observational sheets (Study Two, Study Four). In Study Three, in which phenomenography was employed, phenomenographic interviews were supported with student drawings and researcher generated sheets.

Finally, to confirm the emerging findings, apart from the researcher, at least one of the supervisors was involved. That indicated that the use of multiple investigators was employed as well. For example, in Study One two supervisors, one who was also the course coordinator, were involved in the formulation of the learning task objectives. In Study Two one supervisor participated in the tutorial design and data analysis process. During the phenomenographical analysis in Study Three, two supervisors contributed in the process of formulating the categories of description.

Apart from the results that were descriptive (qualitative) in nature, some results were quantified as well.

Table 5.1. The triangulation based upon multiple techniques involved in the research and across different studies.

Technique	Study			
	One	Two	Three	Four
Stimulated recall interviewing	✓	✓		✓
Phenomenography			✓	
Observing	✓	✓		✓
Document analysis	✓		✓	
Biographical collection	✓	✓	✓	✓

5.2. RESEARCH DESIGN

The four studies of this research are connected to each other in the sense that the findings of a study are used as a rationale in the study that follows. Therefore, the overall design of the thesis is longitudinal in character.

The sections below describe the ways participants were selected, the ways data were collected and the ways the analysis took place in the studies described in the thesis.

5.2.1. Sample Selection

In the studies of this thesis the sample from which the information was obtained was drawn from the realistically accessible population (Fraenkel & Wallen, 1996), which were the first year undergraduates at Massey University who were doing chemistry courses: in 1997 for Study One, in 1998 for Study Two, in 1999 for Study Three and in 2000 for Study Four.

Students who are enrolled in a chemistry course and who use chemistry software are those from whom, according to Merriam (1998, p. 61), most can be learned about chemistry software effectiveness in student learning. This strategy of sample selection is known as purposeful sampling (Fraenkel & Wallen, 1996; Merriam, 1998; Mertens, 1998). Mertens (1998) described that researchers working within the interpretive/constructivist paradigm have used purposeful kinds of sampling.

In most qualitative studies a small number of participants result in a large amount of data. How much data will be collected depends more on the techniques employed (the description of the techniques follows), and the quality of the data already gathered, rather than on the number of participants only. According to Merriam (1998, p. 64), the number of participants in qualitative studies depends on the research questions being asked, the data being gathered, the analysis in progress and the resources the researcher has to support the study. In addition, Lincoln and Guba (as cited in Merriam, 1998) recommended “sampling until a point of saturation is reached”, in which “the sampling is terminated when no new information is forthcoming from new sample units” (p. 64).

A small number of participants was used in each study (Mertens, 1998). In the studies that explored student use of software, more students participated in Study One compared to those in Study Two and Study Four respectively. This was the case because Study One addressed four different software tasks and participants were required for each task. Study Two and Study Four respectively referred to student use of the same in-house authored tutorial. The data being gathered and the analysis in progress in Study Two informed about the number of participants in Study Four.

In Study Three phenomenography was used. Decision about the number of participants

followed other studies in which phenomenography was used with 20 –30 participants being involved. The criteria about ‘sampling saturation’ were employed (Lincoln & Guba, 1985).

The following criteria were considered in the sample selection in all four studies:

- Only volunteers were considered. For the particular part of the research, all students who were enrolled in the current first year chemistry course were invited to participate. Two approaches were undertaken. In one, the oral invitation for volunteers was given before the regular chemistry lecture class started and the ‘call for volunteers’ sheets were left at the lecture bench so the students willing to participate could take them. In another, the researcher visited different laboratory streams and the oral invitation for volunteers was given before the regular laboratory class started. The ‘call for volunteers’ sheets were left at the laboratory bench so students willing to participate could take one.
- Because of the nearly equal proportion of females and males in the first year chemistry courses population, a strategic attempt to balance gender was undertaken. For example, if more females already participated, for the further selection the researcher made a decision to visit laboratory classes with more males. However, because only volunteers were considered, the gender distribution of the participants did not always represent the gender distribution of the population from which the participants were taken.
- Students enrolled in chemistry courses differed in their chemistry background and age, from those who finished 7th Form Chemistry a year ago to those who, for example, finished 6th Form Chemistry a few years ago and took catch-up courses before commencing the chemistry undergraduate course. The chemistry software was aimed to be used by all students enrolled in the course. In order to reveal the effectiveness of chemistry software on student learning across population, it was important that the participants in the research also differed in their background and age.

Participants filled the ‘call for volunteers’ forms and handed them to the researcher, who then made individual phone calls for individual appointments.

5.2.2. Techniques of Data Collection

Study One, which explored student use of commercial chemistry software, combined stimulated recall interviewing, observation analysis and the document analysis (student laboratory reports, researcher's field notes).

Study Two involved two phases, a tutorial **development phase (a)** and a **research phase (b)**.

In phase (a) designing of the stereochemistry computer-based tutorial took place.

Three group members, the chemistry course coordinator (who was also the chief supervisor), the chemistry computer technician and the researcher were involved in the design of the computer-based stereochemistry tutorial. As described in Chapter 3, sections 3.1.4. and Chapter 4, section 4.3. respectively:

- stereochemistry is a chemistry topic difficult to understand and not sufficiently explored, particularly at the university level;
- computers could provide students with an interactivity with models and hence with an opportunity to practice skills similar to those used in remedial tutorials to improve student visualisation, a requirement identified as necessary to understand stereochemistry.

In addition to the reasons described above, the students' feedback to the concepts of stereochemistry, as experienced and described by their lecturer (who was also the course coordinator and the supervisor), indicated that stereochemistry would be an appropriate topic for the software development.

In designing of the tutorial apart from the selection of the topic, particular attention was given to the features of software design.

Structurally, the tutorial consisted of a glossary of stereochemical concepts and three exercises (Exercise One – Exercise Three) that explored the same stereochemical concepts using increasingly complex molecules. The glossary enabled the student to check the meanings of different stereochemical concepts while progressing from Exercise One to Exercise Three.

Other features of software design employed in the tutorial enabled the student free navigation through exercises and from each exercise to the glossary and the interaction

with different representations used for organic molecules (2D-skeletal structures and the 3D-ball and stick interactive models). A detailed description of the tutorial design is given in Chapter 7.

The research phase (b) of Study Two explored student use of the in-house authored computer-based tutorial. In addition and as a complement to the stimulated recall interviewing and observational analysis, observational sheets to record the student responses to each individual task in the tutorial were also developed and filled in by the researcher as the task performance took place.

Study Three explored students' conceptual knowledge and approaches to learning relevant to stereochemistry, the topic addressed by the tutorial in Study Two. Phenomenographical interviews were combined with the document analysis in which student drawings and the researcher-generated documents were used.

As in Study Two, **Study Four** involved two phases, a **development phase (a)** in which the amendments of the tutorial authored in Study Two took place and a **research phase (b)**, which explored student use of the amended stereochemistry computer-based tutorial.

In phase (a) the amendments of the computer-based stereochemistry tutorial have drawn on the results of both Study Two and Study Three. From the insights of Study Two, some technical improvements in the tutorial have been made, and from the insights of both Study Two and Study Three the tutorial was revised to provide more adaptive feedback. Using the findings of Study Three an additional exercise, with animation that addresses the properties of stereoisomers, has been developed. All the amendments were made by the researcher.

In the research phase (b) of Study Four, stimulated recall interviewing was accompanied by tape observation and document analysis in which the observational sheets were used. The method as used in Study Two was used in this study, but because of the new exercise that was added to the tutorial, an additional observation relating to this exercise was added to the observational sheet.

The approach undertaken in all studies of this thesis can be described as a multiple method approach (triangulation) in which interviewing, the primary source of data collection, is accompanied by observation (e.g. from videotapes) and document analysis in which field notes or/and documents (student laboratory reports or researcher

generated observational sheets) were used. Stimulated recall interviewing itself, as employed in this research, could be described as a combination of multiple methods, in which interviewing and observation of the recorded tape were accompanied with field notes or researcher generated observational sheets.

Bibliographical data collection such as the chemistry background of the student before entering the university or student course/exam results were used to check the profiles of the participants in all studies (see for example the list of the participants in Study Three in Appendix 5, CD ROM Appendices). Also the researcher's field notes contributed to all studies. Because those were used as additional data they are not described in more detail.

The techniques used in the studies in which the student-software task interaction was explored (Study One, Study Two and Study Four) were similar. However, the techniques employed to investigate students' ideas in Study Three differed from those employed in other studies. The techniques employed for different studies are introduced below.

(i) Study One, Study Two and Study Four Data Collection

(a) *Stimulated Recall Interviews*

Stimulated recall interviewing was used in the studies that explored student-software interaction (Study One, Study Two, Study Four) and involved video recording of student task performance and subsequent replaying of the videotape to stimulate student recall of learning and thought process. This provided the researcher with an opportunity to subsequently review the task performance. The stimulated recall interviewing dates from the early 1980s when it was used to study the thinking of teachers and students during instruction (Edwards & Marland, 1984; Winne & Marx, 1982). O'Brien (1993) maintains that stimulated recall interview and think aloud protocols are the two main methods that have been used in attempts to find out what goes on inside students' heads while they are learning. Although the stimulated recall interview procedure is not as likely to produce complete and accurate data as concurrent think aloud protocols, stimulated interviews do allow students to do a task in a more natural setting. Therefore, both techniques have strength. The touted advantage of think-aloud protocol is its claim of the possibility to access the actual thoughts the student had when doing the task,

while the conventional stimulated recall interview does not. However, by carrying out the interview immediately after the task is completed, and using the videotape as a stimulus for a student's recall, such as used in these studies, it is possible to explore the student's thoughts in stimulated recall interviewing as well. With students working in pairs, firstly, the stimulated recall interviewing enabled students to do a task in a natural setting and secondly, the immediate individual interviewing enabled the individual participants to recall and comment on both the task and the group work. The technique produced fabulous audio and video-recorded data that could not be achievable by the think aloud method.

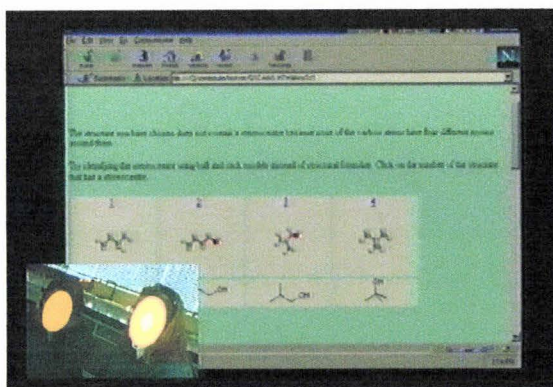
Furthermore, stimulated recall interviews enabled the researcher to explore issues of interest in relation to specific episodes on the video. Sometimes these stay hidden in a think aloud protocol. A stimulated recall interview provides an additional experience for students as they watch the replay of their task performance. These new experiences quite often include new insights into the concepts for the students or clarification (learning) that they have not experienced before.

In the studies that explored student interaction with software (Studies One, Two and Four), the students were videotaped while performing the task and the picture was combined with an image of the computer screen (having recorded student's manipulation of the screen objects), to form a split-screen image on one tape. Figure 5.1. shows a split-screen image showing both the computer-screen (task and student responses) and the student/s performing the task.

A split-screen image showing both the computer-screen (task and diverse on-screen responses such as answer, pathway of progress etc.) and the student/s reactions (with body language and student-student conversation if working in group) when doing the task, was used as a stimulus for both the researcher and the student.

As the task took place, the researcher observed the mixed split-screen tape and noted the significant events, such as:

- student behaviour (e.g. laugh, time spent on task),
- student-student conversation if working in pairs,
- student responses to the computer tasks (e.g. answers to questions, navigation through tutorial, the mouse manipulation in groups).



Paylinic, 1999

Figure 5.1. Combined video of students performing the task and the computer screen image.

The researcher's field notes were then used to select a variety of episodes to check student experiences or student achievement of the task objectives during the subsequent stimulated recall interview. Immediately after the task, the students were shown their task performance tape and simultaneously interviewed. The observed split-screen tape enabled the students to recall the thoughts, strategies, reasons and actions they employed in task performance. In this research, the interviews in which the students talked reflectively about their task experience were also videotaped.

Figure 5.2. shows how the tape stimulated a student to talk reflectively about the task.



Paylinic, 1999

Figure 5.2. Student talks reflectively during the stimulated recall interviewing.

In the studies that involved stimulated recall interviewing the interviews were semi-structured (also called loosely structured, unstructured or minimally structured interviews). Fontana and Frey (1994) suggested that such interviews are preferred in a

qualitative study as they minimise the researcher's (interviewer's) influence and allow the participants a more informal or more natural setting. At the same time this kind of interviewing enables a researcher to get insights into the preestablished question but with a wider range of response categories (Fontana & Frey, 1994; Mertens, 1998).

The tape the student watched during the interview and the researcher's notes (field notes in Study One and observational sheets in Study Two and Study Four, described later) slightly shaped the ways the researcher collected data (i.e. each individual interview). From one point, while observing the combined tape during the task performance, the researcher recorded episodes/aspects/problems in individual observational sheets (or field notes in Study One). The aspects recorded in the observational sheets shaped the interviewing process because they were targeted for clarification during the interviews. From another, the individual participants commented on their own on what they had learned or discussed, what they found difficult or helpful during the task performance. Stimulated by watching the tape the students were able to recall the episodes and talk freely on their own. For these reasons the semi-structured interviews differed from one participant to another.

(b) Observation Techniques

Merriam (1998) described that observations are a primary source of data in qualitative research. Both Merriam (1998) and Mertens (1998) describe qualitative observation occurring in naturalistic settings without using predetermined categories of measurement or response. Also, Merriam (1998) highlighted that observational data represent a firsthand encounter with the phenomenon of interest while the data obtained in an interview represent a second hand account of the world.

Observation is described as especially powerful when combined with other methods (Denzin & Lincoln, 1994). In the studies (One, Two and Four), the observation was carried out:

- Observing the videotape (with the split-screen images of the computer screen and the student performing the task) by the researcher during task completion, prior to the interview (as indicated earlier, the interview protocol was slightly shaped as a consequence of the observation and comments recorded in observational sheets);
- Observing both the videotape of task performance and the videotape of the

interview after the other data were collected and combining observation with other data gathering procedures (interviews and documents) to yield depth and/or breadth, as well as to enhance consistency and validity. The videotapes provided the researcher with the opportunity to observe it repeatedly.

According to Merriam (1998), in the real world of collected data, interviews and conversations are often interwoven with observations, and the terms fieldwork or field study connote both activities.

(c) Document Analysis

Different documents were used in the studies that explored student use of software. In all studies described in the thesis, the term document was assumed as described by Merriam (1998) and refers to a wide range of written, visual and physical materials relevant to the study at hand.

In Study One students' laboratory reports were used, in Study Two and Study Four respectively researcher developed observational sheets were used (according to Merriam, 1998, researcher generated document).

Student Laboratory Reports

In Study One three of four tasks that were selected for the study were part of the regular laboratory experiments, for which students were asked to write a written report, including answering questions related to the computer-based tasks. Writing laboratory reports was a compulsory part of laboratory classes and therefore student laboratory reports were documents not produced for research purpose. However, according to Merriam (1998) most researchers find it well worth the effort to examine documents that are already present and that are not produced for research purpose.

The student laboratory reports contained much that is irrelevant to the study, but the answers to the questions related to the computer part of the experiment were provided additional data of their understanding of the task and the concepts explored by the task (for a copy of student laboratory report see Appendix 2, CD ROM Appendices).

Observational Sheets

Observational sheets are additional researcher generated documents that were designed and employed in data collection in the studies that explored student interaction with the

in-house designed computer-based stereochemistry tutorial (Study Two and Study Four respectively). Observational sheets were designed to enable the researcher to write the field notes as the task performance took place and to use them to focus on specific aspects of performance during the subsequent stimulated recall interviewing (for observational sheets see Appendix 4 - Study Two and Appendix 6 – Study Four, CD ROM Appendices).

In conclusion, stimulated recall interviewing as a technique and as employed in these studies, is a multi-method that integrates observing, interviewing and document analysis. This kind of multi-method approach enabled the recording of non-verbal features of interaction as well as the consonance between verbal and non-verbal features. The three techniques were interwoven and often used simultaneously, however, the priority was given to the data collected from the interviews, followed by the observational techniques and document analysis.

(ii) Study Three – Phenomenographical Data Collection

The phenomenographic approach was employed in the data gathering and data analysis process in Study Three (Marton, 1981; Marton & Booth, 1997; Marton & Säljö, 1984). Marton and Booth described that phenomenography as a research approach explores an internal person-world relationship through the second-order perspective in which the researcher investigates the statements (descriptions) about the world, phenomena or situations as experienced by the people. Phenomenography as a research approach and theory of learning is described in Chapter 2. The literature suggests that this method of collecting and analysis of participants' discourse is particularly suitable for describing the ways of experiencing phenomena. For that reason, phenomenography was chosen to identify the student conceptions related to the topic addressed by the in-house authored tutorial designed in Study Two.

Marton and Booth (1997) described how the phenomenographic approach presupposes the following constituents of any experience (learning):

- In a learning situation there is an intertwined experience of a phenomenon and a situation (a context, a time and a place);
- There are two aspects of learning, the *what* aspect and the *how* aspect of learning. While the *what* aspect of learning refers to the content that is being

learned (direct object) the *how* aspect of learning refers to the act of learning.

- Any experience has a structural aspect intertwined with a referential (or meaning) aspect. The structural aspect is twofold, discernment of whole from the context on the one hand and discernment of the parts and their relationship with the whole (this is conception) on the other hand. The former is described as the external horizon, while the latter as the internal horizon of the experience.

These constituents of the experience should be considered in any analysis based upon phenomenographical approach.

A limited number of hierarchically ordered categories of description (for example the given ways in which the participants experienced phenomena) is the outcome of the phenomenographic analysis (Bowden, 1994; Marton, 1981; Marton & Booth, 1997; Marton & Säljö, 1984; Walsh, 1994).

As phenomenographic analysis and the way the categories of description are derived out of data involves the constant comparative method, in which emerged categories are compared to each other within and between the levels of conceptualisation, Richardson (1999) argues that the analytic procedures of phenomenography are very similar to those of grounded theory.

To explore student conceptions related to stereochemistry, a topic addressed by the in-house authored tutorial designed in Study Two, phenomenography, as employed in this study, involved data gathered from the interviews supported by the documents; in this case the student drawings and student responses to researcher-generated sheets. The researcher made notes as interviewing and observations took place, but the additional notes were added immediately after the interviews were completed. Also, bibliographical data collection, as described for other studies (Studies One, Two and Four), was used as well.

(a) Phenomenographical Interviews

This study differed from the studies which explored student use of software in which student responses on computer screen played a very important role in collecting and analysing data. This part of research aimed to explore student conceptions in which the amount and quality of verbal data as well as the descriptive analysis are of the most importance. For that reason, in this study all data were collected by face-to-face audio

taped and verbatim-transcribed interviews.

Most studies that employed phenomenography as a research approach employed the audiotape interviewing process. Apart from the amount and quality of the verbal data collected during the interview, the set up of the audiotape interviewing was easier when compared to the one employed in stimulated recall interviewing.

The use of video recording such as that employed in stimulated recall interviewing in Studies One, Two and Four showed one disadvantage of the method, namely the need for a number of recorder devices. For example, a mixer device to make split-screen images, Multigen Pro, and a device to input computer screen image had to be borrowed from other departments, set up in advance, and checked before the student/s arrived.

In audio-taped interviewing these problems were not present. However, audio taping interviews missed the opportunity for the observational techniques that the video taping provided. Some of the data were lost. For example, only the researcher's field notes informed about student manipulation with the ball and stick models during the phenomenographical interviews.

Phenomenographical interviews can be described as conversational or exploratory interviews. While some structure was developed prior to the interviews, this provided a broad guide only. Phenomenographical interviews allowed the interviewees to express their own relation with the world. Detailed description of the phenomenographical interviews is given in Study Three, Chapter 8.

An example of the interview transcript from Study Three, which explored the student conceptions relevant to stereochemistry, is given in Appendix 5.

(b) Document Analysis

Data emerged from the phenomenographical interviews were accompanied by the diagrams students drew during the interviews and by data given when students responded to the supplementary sheets.

Student Drawings

In Study Three, during the interviews, the students were asked to describe the ways in which they visualise a particular molecule (2-butanol). They were provided with a pencil and a blank paper sheet and all participants made drawings to illustrate their

conceptualisation (see Appendix 5).

Researcher Designed Sheets

The supplementary sheets with different representations of chemical compounds were designed in Study Three to elicit a verbal response from the student about the concepts addressed in the in-house authored tutorial, designed in Study Two (see Appendix 5). They were part of the structure that was developed prior to interviews. The development of the sheets followed the conceptual structure of the in-house developed tutorial (Study Two) and the learning objectives that were set up in study guide for the unit addressing isomerism. The sheets included:

- the diagrams of different molecules (SO_2 , 2-butanol) aimed to elicit student understanding of different representations and to compare these responses to their visualisation described earlier;
- the diagrams of different isomeric relationship between molecules, aimed to elicit student awareness of different types of isomerism.

During the interview these sheets were shown to students to collect their responses.

The drawings produced by students during the interviews and the supplementary sheets that were shown to the students are examples of research - generated documents. When combined with other research information sources they enrich depth and/or breadth of the findings and enhance their consistency and validity.

(c) Observation

In Study Three, the observation was interwoven with the phenomenographical interviews. On the basis of what was observed during the audiotaped interviews, the researcher made field notes.

5.2.3. Data Analysis

The analysis of the data in all studies of the thesis can be described as descriptive analysis which involved the constant comparative method (developed as “grounded theory” by Glasser and Straus since 1967). According to Merriam (1998, p.18) “the constant comparative method of data analysis is widely used in all kinds of qualitative studies, whether or not the researcher is building a grounded theory”. It is suggested

that phenomenography, which was employed in Study Three, also has very strong elements of the constant comparative method (Richardson, 1999).

While the detailed description of the data administration and the analysis process in each study is given in the appropriate chapter, the main principles are described below.

(i) Study One Data Analysis

The aim of this study was to investigate how students interact with different kinds of commercially available software, used in a first-year undergraduate chemistry course. The analysis of the data in this study can be described as a step-by-step process (as described by Merriam, 1998, pp. 180-182), in which the constant comparative method was employed and involved “comparing one segment of data with another to determine similarities and differences” (for example, one quote with another quote by the same or another participant). According to Merriam (1998, p.18) the data analysis starts by grouping data “together on a similar dimension”. When the dimension is tentatively given a name it then becomes a category. The overall object of this analysis is to seek patterns in the data and to arrange the patterns in relationship to each other.

In Study One, for each task and for each participant/group of participants a set of data was available. For example one set of data, coded ***p-V* Experiment, simulation, Task 1, Bill** (title and type of software, number of task in the study, participant pseudonym), included:

- the verbatim transcript of the stimulated recall interview,
- the videotapes of both the task performance by the student and the interview,
- a copy of student laboratory report in which student provided the answers to the questions related to the computer-based part of the experiment,
- the researcher’s field notes.

For the participants working in groups, a transcript of student-student conversation was also available (see Appendix 2 for one set of data that involved the transcripts of both the student-student conversation and the interview, accompanied with a copy of the laboratory report).

The analysis started from the reading of the first interview transcript and replaying the videotapes (the task performance tape and the interview tape) in conjunction with the

transcription, field notes and the student's laboratory report. This first step of the analysis ended in a list of items (terms, comments, notes) that emerged from the first set of data (a list of items that derived from one set of data is given in Chapter 6 which describes Study One).

The same process of analysis was repeated with the next set of data (another list is also given in Chapter 6). The comments grouped and listed from this set of data were compared with the list made from the first set of data. The two lists were merged to give some patterns that could occur in the study. As the process moved on and involved more and more sets of data, the pattern of regularities within the task became apparent.

After all sets of data related to one task were completed, the analysis moved to the next task until all sets of data for all tasks were completed.

The process of regularities that was first observed within one task now became apparent when the data from different tasks were combined. These apparent regularities became the themes into which different items were sorted.

Therefore, the next step of the analysis involved differentiation of themes and the description of its relevance to the student use of software. One theme combined items that were specific for a particular task, the other theme merged items that gave more general insights about student use of the software.

The final step of analysis involved the evaluation of the effectiveness of each piece of software application on student achievement of the selected target objectives. The evaluation was made for each previously identified theme.

All steps of the analysis are described in detail in Chapter 6.

The analysis started from the lists of individual student responses and ended with broader, more general conclusions about students' use of chemistry software. This is in agreement with what Fielding and Schreier (2001) described sequencing, a part of a qualitative research strategy when qualitative research wishes to go beyond individual cases and say something about the sample at large, maybe even the whole population from which the sample was selected. Sequencing is taking place whenever a generalisation of qualitative findings occurs and according to Fielding and Schreier, sequencing constitutes an inherent characteristic of many typically "qualitative" approaches (such as grounded theory).

The method employed also enabled the researcher to quantify student responses for each of the aspects identified. Reviewing triangulation as the combination of qualitative and quantitative approaches in the data analysis process, Fielding and Schreier (2001) described how two situations are possible. One would be a quantitative phase which is followed by a qualitative phase of analysis and the other would be a qualitative phase followed by a quantitative phase of data analysis, such as employed in this study.

(ii) Study Two Data Analysis

Study Two involved the designing of a computer-based stereochemistry tutorial and aimed to investigate how students interact with an in-house authored computer-based tutorial of chemical concept – centred design.

The method involved stimulated recall interviewing and collection of additional data for which techniques were developed in Study One. In addition observational sheets were developed in Study Two and were also used in Study Four. The observational sheets followed the structure of the tutorial and enabled the researcher to enter field notes while observing student progress through the tutorial and student responses to the software design. Completed sheets were used during the stimulated recall interviewing to focus on the episodes in which the student showed most difficulties.

In the data analysis process the completed observational sheets were used together with the videotape observations and the transcripts of the interviews (and student-student conversation if worked in groups).

A step-by-step process, similar to that described in Study One, was employed in the data analysis of Study Two. The analysis focussed on how the design features of the tutorial influenced the student use of the tutorial and the student achievement of the selected task objectives. The observational sheets with individual student responses added a new dimension of analysis – student progress through tutorial. Detailed description of data analysis is given in Chapter 7, which describes Study Two.

(iii) Study Three Data Analysis

The aim of this study was to investigate the relevant conceptual knowledge and approach to learning which students bring to the computer-based tutorial, and it involved three phenomena:

- to find out the ways students visualise molecules and to find out if the representations for molecules used in the computer-based stereochemical tutorial (made in Study Two) match the students' conceptions;
- to find out how students relate their visualisation to a macroscopic sample of the substance;
- to find out students' conceptions of different isomer types.

It was planned that the findings from this study be used as the basis for making amendments to the stereochemistry tutorial, in the phase of the thesis that follows (Study Four).

It was described that phenomenographical interviews, audio taped and verbatim transcribed, were supported by the researcher generated documents such as student diagrams, supplemented designed sheets with different representations of chemical compounds and field notes written during and immediately after the interviews.

In this study, analysis started with the reading of the individual interview transcripts repeatedly and analysing student drawings. Student responses to prepared supplementary sheets with the representations of the organic compounds were compared to the verbal description and drawings given by the student at the beginning of the interview. Transcriptions were considered together with students' drawings and the researcher's field notes. Relevant utterances were selected and combined to form a pool of meanings.

In the second stage, attention was shifted from the selected individual student quotes to the meanings embedded in the quotes, regardless of whether these different meanings originated from the same individuals or not. A step-by-step differentiation within the pool of meanings was the next stage of the data analysis process. As a result of this interpretative work, students' quotes or utterances were brought together into categories on the basis of their similarities and differences. The process of identifying categories involved two steps. Firstly, the quotes were sorted into piles, borderline cases were examined and eventually criterion attributes for each group were made explicit. At that stage, quotes were arranged and rearranged and narrowed into categories. Secondly, categories were defined in terms of core meanings and differentiated from one another in terms of their differences. Once the different categories of description were formed, they were analysed in relation to each other and placed at specific levels in a logically

structured hierarchy.

The researcher and two supervisors, for two of the phenomena investigated in the study, read the transcripts independently and discussed and negotiated categories. Detailed description of the phenomenographic data analysis for each phenomenon is given in Chapter 8.

(iv) Study Four Data Analysis

Study Four involved revision of the computer-based stereochemistry tutorial that was designed in Study Two and aimed to investigate how students interact with an in-house authored, chemical concept – centred computer-based tutorial, amended to take account of student prior knowledge and approach to learning.

Two faces of the tutorial amendments (the minor in which technical amendments, based on the results in Study Two, were made on three initially designed exercises and the major amendment, in which an additional, Exercise Four, was added to the tutorial on the basis of the results in Study Three) generated two aspects of the analysis in this study. The label “minor” amendments was not used to diminish the importance of these amendments. They were significant and worthy of evaluation. However, unlike the major amendment with added Exercise Four, the minor amendments did not change the structure of the original design.

The first aspect of analysis aimed to reveal whether or not the minor technical amendments done in the design on the three exercises in the tutorial (the design characteristics in Study Two were described as those that influenced the student in achieving selected learning objectives when using this software) made any difference when compared to the findings in Study Two.

The analysis started with a selection of the aspects that were identified as critical during the student-tutorial interaction in Study Two. Therefore, in this stage, the analysis of the amended three exercises of the tutorial (Exercise One – Exercise Three) was similar to the one in Study Two. The observational sheets, the interview transcripts and the tape observations were used in this part of analysis.

The second aspect of analysis focussed on the major amendment done in the tutorial – student responses to the added Exercise Four that emerged as a separate theme. All student responses to this exercise that addressed the properties of stereoisomers were

pooled together. Student verbal responses were, particularly for this added exercise, accompanied by the use of body language (for example the use of hands to illustrate direction of the rotation, sometimes to support words, sometimes instead of words). For this reason, the evidence observed on the videotapes supported the interview transcripts (and transcripts of student-student conversation if worked in groups).

Using a constant comparative method, student verbal responses were grouped according to the aspects participants were talking about. For example, one group of student responses included student verbal and emotional responses to the design of this exercise, which differed from the design of the other three exercises (in Exercise Four a design of guided discovery and animation were employed). Another group of student responses included student discourse in which they discussed about properties of enantiomers, the third group included students' discussion about properties of other stereoisomers etc. These different groups of student responses became different dimensions of this theme. Each of the dimensions was further analysed to notify about the specific experiences and knowledge students gained doing this exercise.

The procedure of analysis used in Studies One, Two and Four was developed as the research was carried out. The detailed data administration and data analysis process for this study are given in Chapter 9.

5.3. ETHICAL ISSUES

The Oxford English Reference Dictionary (Pearsall & Trumble (Eds.), 1996) defines ethics as:

- 1) the study of morals in human conduct; moral philosophy. 2) the rules of conduct recognized as appropriate to a particular profession or area of life. (p. 481)

Any researcher needs to consider the ethical questions relating to his/her research and, as Fraenkel and Wallen (1996, p. 37) anticipated, think about the question "Will any physical or psychological harm come to anyone as a result of my research?" In studies described in this thesis the ethics concerned the immediate participants taking part in the study. Burgess (1989) indicated that ethical issues are involved in all aspects of research from initial research design and formulation of the research problem through to the point of publication. It is particularly important for a researcher to protect

participants from harm and also to ensure confidentiality of research data (Fraenkel & Wallen, 1996).

Researchers need to regularly reflect on their work and develop an understanding of the ethical implications associated with social and educational investigations (Burgess, 1989). Burgess pointed out that ethics is an issue in our daily activities not only as researchers, but also as teachers, students and practitioners and quoted Cassel and Jacobs (1987) who highlighted that ethics should be considered not only in exceptional cases but in everyday decisions, in reflecting not only upon the conduct of others but upon our own actions. One such example of ethics in teaching and doing science is described by Sweeting (1999) who developed the course Professional Ethics for Scientists for undergraduate students, which enabled the students to reflect on their practices and values (views) and the teachers to examine the way they do and report science, and the methods they use for teaching and examining students. The individual and group discussion during the course enabled both sides to learn from each other.

The research protocol for this study was submitted to and approved by the Massey University Human Ethics Committee (MUHEC). MUHEC's Code of Ethical Conduct for Teaching and Research involving Human Subjects is relevant for any teaching or research involving human participants. The research protocol and the Massey University Human Ethics Committee approval are given in Appendix 1, CD ROM Appendices.

5.3.1. Protection of the Participants Involved in the Thesis

According to Merriam (1998) in qualitative studies, ethical dilemmas are likely to emerge with regard to the collection of data and in the dissemination of findings. Consideration of both describes the researcher – participants relationship and is determined by “how much the researcher reveals about the actual purpose of the study, how informed the consent can actually be, and how much privacy and protection from harm is afforded the participants” (p. 213).

The studies reported in this thesis involved an interactive approach in which the researcher orally introduced

- herself and her task as a researcher which was to gather data only and not to evaluate participants' knowledge or change them (pre and post tests were not used);

- the purpose and the nature of research undertaken – students were given an outline of the overall project and the current study/stage of the project;
- the nature of the task in which they should be involved – which is a part of the first year chemistry course;
- the participant's position and the participant's role - students were informed about their volunteering position and the role of contributing towards the advancement of knowledge;
- their own benefits – students were told that the only benefits of participating could be in a form of the insights gained into their thought process while carrying out the task or talking about it (Merriam described "*some gain valuable self-knowledge*", 1998, p. 214) and that no additional credits in the course could be gained. The students were also assured that there were no penalties for not participating in the research. During the participant selection, there was a case in which the information of no additional credits in the chemistry course prejudiced against participation.
- the nature of participation - they were informed about the nature of their participation (e.g. interviewing, video recording);
- the participants' protection in the research and their rights – they were informed about participants' anonymity by the use of pseudonyms in transcription. They were also informed about their rights to withdraw from the project at any time.

All this information was orally given before signing the consent form and commencing the participation. The researcher also verbally answered all questions raised by the students, regardless of those who participated in the research or who did not. The same information was also individually given in a written form in both the information sheet and the consent form.

No participation in the research had taken place before each participant had read the information sheet, felt comfortable about the research and his/her own participation and signed the consent form (copies of both, the information sheet and the consent form are given in Appendix 1).

(i) Ethics in the Data Collection

According to Merriam (1998), the standard data collection techniques in qualitative research are interviewing and observation and both of them involve ethical dilemmas. In addition to interviewing and observation, in three studies described in this thesis, videotaping was employed too. This was an additional ethical concern that was clearly outlined in the informational sheet and the consent form.

The participant's right to withdraw from the research was assured too. Participants were shown the control commands on camera and video-recorder so that they were able to stop recording at any time if they felt uncomfortable. Also, during the interview in Study Three, the tape recorder was placed in front of the participant and not the researcher.

All the participants were volunteers. Although according to Merriam (1998, p. 214) "most people who agree to be interviewed enjoy sharing their knowledge, opinions or experiences", the author also pointed out that sometimes in interviewing, the participants may be embarrassed by certain questions (for example the feeling that they are judged on their answers which they may not feel very confident about). Merriam (1998) suggested that an interview may improve the condition of the respondents when, for example, they are asked to review their successes or are stimulated to act positively on their own behalf (p. 214). This occurred in the stimulated recall interviewing as students were asked to review their own interaction with the computer-based tasks by watching the mixed tape showing both their behaviour and their responses to the computer screen. Students were able to comment on their answers and actions on their own initiative, rather than being asked. They were only asked to comment on the aspects, recorded in observational sheets for example, if they did not comment on them unprompted.

The analysis of the recorded videotapes (observation) suggested that initially students were aware of the purpose of their participation and the researcher's presence. However, the same analysis suggested that as the task performance took place, the majority of the students seemed to become less aware of the researcher's presence as soon as they became engaged with the tasks. Only one participant in Study Two commented on being frustrated by the presence of the camera.

The videotapes have recorded the students' faces. In the cases where the tapes are used,

the participants are protected by having their faces blocked out (see Figures 5.1 and 5.2.). Once transcribed with the given pseudonyms, to ensure the anonymity of the participants all the tapes were stored to be destroyed.

As Merriam (1998, p. 214) described, the interviews can help some students gain valuable self-knowledge. After participating in Study Three, many participants visited the researcher to express their satisfaction with the interview in which they were prompted to think about the phenomena in a way they have not in the past.

(ii) Ethics in the Data Analysis and Dissemination

Merriam (1998) stated that analysing data might present other ethical problems because the collected data have to be filtered through the researcher's particular position and biases although sometimes these biases are not readily apparent to the researcher. According to Merriam, there are simply no practical guidelines for the situations a researcher can face and there is no ethical alternative to attempting to be as unbiased, accurate, and honest as is humanly possible in all phases of the research. The only way to limit undesirable effects is through the use of careful planning, conducting, analysing and reporting of the work, and the use of methodological controls (Merriam, 1998, pp. 212-219). Data source triangulation was employed during the research, and all data were checked with the supervisors during the data analysis process.

The researcher had Massey University (MU) employment in the area of investigation. To the researcher's knowledge, there was no direct influence of the research funder (MU) in any of the steps of the research. Massey University as an institution has directions to follow and compete at the international level, so the focus of the thesis could be in line with revealing the quality of the education the university provides and investigating the ways of achieving the best quality, one of which is computer-based learning. In addition, market demands today require the technology engagement at all levels, so the project followed that line in education.

Apart from the researcher and her supervisors, no one controlled or influenced the way the research was conducted. A concern might be the indirect influence that MU had on the supervisors and the way they influenced the research. Two supervisors are chemistry lecturers and they were the course coordinators for the two first year chemistry courses, at the time the research was carried out. The tasks for investigation were taken from the two courses, Chemistry I (a) and Chemistry I (b), and the

participants were selected from those enrolled in the courses. The researcher was aware of the enthusiasm for computer-based learning shown by one supervisor who initiated the project. It might be that the supervisor's power initially influenced students' decision to take part in a particular study because he was also their chemistry lecturer. Also, initially, the researcher's contact information (name, phone number, office number), and the contact information of the supervisor, who was also their lecturer and course coordinator, were both written on the call for volunteers sheet.

However, at that initial stage it was of particular help to the researcher who was new at Massey University (and in New Zealand too) and who had English as a second language. It provided an easier communication with the students. As the project progressed the researcher became more confident in the research. The approach to select participants was changed from visiting lecture classes to visiting laboratory classes (in the later stage, no supervisor's information was given on the call for volunteers sheet).

Apart from that, no other concerns were identified.

5.3.2. Participants – Researcher Relationship: Discussion

The decision was made to inform and include all students enrolled in the chemistry course. For that reason, at the beginning of each study (which coincided with the beginning of the semester) students were introduced to the project, a part of the project or a particular study and invited for participation. Initially, students were approached before the lecture started (orally and the call for volunteers sheets were left at the lecture bench so those willing to participate could take them). Later the decision was made to approach students and select participants from laboratory classes.

For most studies the participants were selected from the laboratory classes. Multiple reasons led the researcher to that choice.

1. The laboratory classes were a compulsory part of the course; so all students enrolled in the course were accessible.
2. Students were grouped in laboratory classes according to the other papers they attended. Approximately 25-30 students were present in each laboratory class. For the researcher, it seemed easier to introduce herself and the research undertaken, and to ask for volunteers in front of the laboratory class group rather

than the lecture class group (about 150 students). It was more likely that students in smaller groups would pay more attention to the researcher, who is not their 'well known' lecturer or laboratory supervisor.

3. The laboratory class allowed the researcher to make more direct, personal contact with students and to answer immediate questions raised by the students.
4. The possible selection of participants according to criteria employed (for example on the basis of the sex) was easier in small groups. For example when the number of male participants outnumbered the number of females, the researcher chose the laboratory class with more females.

Merriam (1998) pointed out that wherever the investigator holds great power and control, there is a danger of abuse and thus a great need for guidelines and regulations (p. 213). The researcher was employed as a Graduate Assistant within the Chemistry department at Massey University. According to the Employment Contract the researcher was obliged to supervise no more than two laboratory classes weekly.

Most of the participants were selected from laboratory streams other than those being supervised by the researcher. However, there were some participants from the laboratory streams that were supervised by the researcher:

- It appeared that some of the participants who replied to the invitation given at the lecture were from the laboratory classes supervised by the researcher. In some cases, and at the time students replied to the call for volunteers given at the lecture, the students did not know who would be their laboratory supervisor and the researcher did not know that she would be supervising those students. Because of the initial decision to include all streams so that the most diverse student selection could be achieved, those students were included as well.
- In the situations that the researcher needed an additional participation (to check if the saturation was achieved or to confirm it), the researcher considered the students from her own laboratory streams as well. However, that happened towards the end of the course and the end of data collection for one particular study. To avoid the students feeling obliged to participate in the project of the researcher who was also their supervisor, students were invited for participation during the last laboratory class. As no more laboratory classes took place, the students' decision to participate was very little influenced by the researcher's power.

The researcher did not have access to the students' final records. However, she was a staff member and was involved in the marking of laboratory reports and laboratory tests. The students and particularly those who were in her laboratory classes might have seen the researcher as a member with authority, who makes decisions, at least during the laboratory classes. All students were invited to ask the researcher any chemistry related questions and to visit her in her office at any time. Two cases differed from the others because of the additional student-researcher interactions.

In one case, one member of the laboratory group that was supervised by the researcher used to visit the researcher for help regarding the chemistry problems before taking participation in Study Three. It might be that this participant felt obliged to reply to the researcher's call for volunteers. Or maybe this participant was one of the students who had in mind the possible benefits of choosing to participate in the study.

In the other case, one participant also in Study Three (from the researcher's laboratory class and who replied to the call for volunteers given at the lecture class) visited the researcher after his participation and asked for a print of a molecular model of the aspirin that he needed for some other paper project. It might be that either due to participating in the research and/or being a member of the laboratory class supervised by the researcher, he felt free to ask for that favour. The researcher, who met the participant's request, would do the same for any other student, from any laboratory stream and regardless of whether the student participated in her study or not.

The researcher-participant relationship is a relationship between people and in this case depended on both the researcher and the students. The researcher formed a very good friendship with some participants which remained long after the data collection and the study were finished. One participant in Study One, from a laboratory stream not supervised by the researcher, used to come regularly for help in solving chemistry problems even one year later. Another volunteer, half a year after participating in the research, invited the researcher to join her dancing group.

The researcher's interest in how well the participants did in their final exams was not only because of the need to fill in the background of the participants, but also because of the individual concern that arose because of contact through the research.

5.4. LIMITATIONS TO THE RESEARCH DESIGN

Any research design must recognise its limitations. Limitations include different parameters that arose in the study as a consequence of the research design, from the data collection process and analysis to the interpretation of results.

- The participants in all four studies were volunteers. Volunteers do not necessarily represent the population from which they came. They are for various reasons more interested to participate and might be those as Merriam (1998, p. 214) described who enjoy sharing their knowledge, opinions or experiences. It would be expected that the volunteers are more able students, who have more confidence to come forward. It was encouraging to observe a diverse ability of the participants in all studies.
- Some of the data obtained from one participant in Study Two were excluded because the participant spent all the time exploring the glossary part of the stereochemistry tutorial and has not done the exercises. The stimulated recall interviewing was performed with this participant in the same way as with other participants, so most of the information was collected (about the student's prior knowledge about a topic, familiarity with computer use, preferences for representation given in the tutorial for addressing stereochemistry concepts etc.). The student himself explained that due to his poor prior knowledge in stereochemistry he decided to explore the concepts rather than to do the problem solving exercises. The student's choice was appreciated as the design of the tutorial aimed to meet different students' needs. This was the main contribution of this participant because it confirmed that students may take different pathways through the tutorial in order to reinforce their knowledge of stereochemistry (student-determined pathway rather than tutorial-determined pathway). However, less data related to the exercise part were collected, which is significant since only eleven participants participated in this study.
- The samples were accidental (i.e. those who came forward) and cannot represent the variety of ethnic, age and other demographic characteristic that might be relevant. For example, the ethnic issues were not considered in the studies described in the thesis. All participants but one were New Zealand – European; the participant with Chinese ethnic background was educated in New Zealand. Although some

participants were those with a gap between the high school and the university level, and one participant in Study Four was a very young student, it still does not guarantee that the age distribution of the population from which they were drawn was covered. While the representative age is not an important issue as data do not have to be representative of the population, computer supported learning may make different addition to the learning of various age groups.

- In all studies small samples were taken (in Study One 32 different participants, but distributed across four tasks with some participating in more than one task; 11 participants in Study Two; 25 in Study Three, 14 in Study Four). Although large amount of data were collected, the small number of participants does not allow the generalisation of the findings.

Apart from the general limitations, there were limitations that were specific to the particular study. For example, in Study One, the information gathered from Task 4 was not as extensive in description as that gathered from Tasks 1, 2 and 3. The time constraints allowed short interviews and the participants did not talk as readily as those in other tasks. That might also be due to the complexity of the concept covered by the task (Three dimensional structures of solids) or due to the nature of the computer-based application (video clips).

According to Marton and Booth (1997, p. 165.) “the validity claims of first-order statements concern under any circumstances the validity of our statements about the world” (e.g., to what extent a scientific explanation offers a consistent and useful description of certain aspect of physical reality), while “the validity claims of second-order statements concern the validity of our statements about ways of experiencing the world” (e.g. to what extent a researcher’s account offers a consistent and useful description of a scientist’s way of seeing certain aspects of physical reality).

The researcher herself was a novice in educational research and the lack of experience influenced the way research was conducted. As the research progressed, better managing of the research (from sample selection to analysis) occurred.

Limits of time were present for the project as a whole. The funding was available for three years. The data were gathered throughout three years (from 07/1997 to 06/00). Due to the time taken for data administration (e.g. transcription was very time consuming) and the data analysis for each study, some important aspects may not have

been addressed fully. For example, the participants working in groups with a good cooperation and collaboration produced the most powerful insights, but because this contribution was not the aim of the studies described in the thesis, it was not fully addressed. While the benefits of participation in groups were not mutual for all group members, it is worth acknowledging the enormous group contribution to the research. The student-student conversation during the task revealed data that would never be revealed by the interviewing of individuals only.

In conclusion, limitations of the research design employed in the studies of the thesis are related to the validity and reliability of the findings and those depend on all steps involved in the research design (e.g. findings were collected from small sample numbers or the researcher's position in collecting and analysing data). Merriam (1998) indicated that the concerns about validity and reliability are common to all forms of research, so were present in the research described in the thesis. The researcher followed the suggestions by Merriam (1998), and tried to minimise limitations by ensuring that the investigation is conducted in an ethical manner, that the research design is carefully planned and carried out throughout the research and finally that all steps of the research are described in as much detail as possible.

6. STUDENT USE OF COMMERCIAL SOFTWARE IN A FIRST YEAR CHEMISTRY COURSE – STUDY ONE

Chapter 4, section 4.4. introduced the research problem and research questions that were initiated by the responses from students, studying first year chemistry at Massey University in 1996, who were surveyed on their opinions of computer aided instruction in the course. A small proportion of the students showing enthusiasm (about 10%) indicated a mismatch between the teachers' expectations of what CAI can offer and the ways students responded to what was being delivered. Study One aimed to get insights into the possible reasons for a mismatch observed. The mismatch observed by the survey was exhibited in the first year chemistry classes at Massey University and so this group of students was chosen for the study.

6.1. RESEARCH QUESTIONS OF STUDY ONE

Research Question 1

How do students interact with different kinds of commercially available software, used in a first-year undergraduate chemistry course?

was further refined into a series of questions, formulated to provide the focus for this study:

- 1 a) What achievement do students demonstrate of the chemistry learning objectives in the tasks?
- 1 b) How is student performance on the software-based task affected by:
 - (i) interaction with the software from the point of view of the type of software, implementing instructions, the subject content, the navigational options and the feedback provided?
 - (ii) student prior knowledge?
 - (iii) interactions with other students?
 - (iv) interactions with the computer hardware?

1 c) How do students feel about using computers as a tool to help them learn chemistry?

6.2. SETTING OF THE STUDY

In order to explore the experiences of groups of students using chemistry software within the chemistry course, a qualitative method was employed in this study.

The study was carried out during the second semester of 1997. It focussed on the uses made of computers by students enrolled in the first year paper Chemistry I(b). The paper covered chemical bonding, inorganic and physical chemistry topics and complemented a first semester paper covering organic and physical chemistry. A more detailed description is given in Table 6.1.

Table 6.1. A description for the Chemistry I(b) course (Chemistry I(b), 2001).

Number	Paper details	
123.102	Chemistry I(b)	12.5 points
	<i>Prerequisite/s:</i>	Assumed background is a pass in the Bursary Chemistry examination, a pass in <u>123.103</u> or <u>123.104</u> , or an acceptable alternative.
	<i>Corequisite/s:</i>	none
	<i>Restriction/s:</i>	none
	This paper, which complements 123.101 Chemistry I(a), starts with an introduction to the structure of molecules and molecular orbital theory. The chemistry of materials is then introduced based on compounds containing the main group elements and is followed by a topic on the electronic, magnetic and chemical properties of transition metal complexes. Physical chemistry topics include thermodynamics and electrochemistry, the states of matter, phase diagrams, solutions and colloids.	

<http://sciences.massey.ac.nz/papers/display-paper.asp?ID=266&Paper=123.102>

6.2.1. Tasks

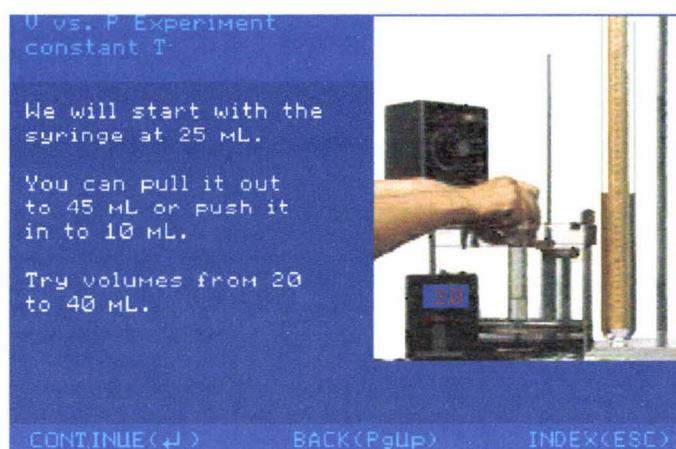
The study involved analysis of performance on four computer-based tasks given to students during the course. Four tasks were selected because they are representative samples of different types of the CAI application used in chemistry and with different aims (a simulated experiment, a supplementary tutorial, a problem solving exercise,

illustrative video clips). The first three tasks were based on commercially available software and the fourth was a task made up using a series of commercially available video animations.

Task 1: A simulated Boyle's Law experiment (Smith, Jones & Gammon, 1992) - In this simulated experiment, students used video images of equipment to collect data for an experiment investigating the pressure-volume relationship of gases and then analysed the data graphically. At the start of the experiment students were getting familiar with the equipment. Then they were directed to the next set of screens in which they performed simulated measurements. The software enabled the students to choose and click at the appropriate button that will, either by pushing in or pulling out the piston inside the syringe, simulate the change in the pressure of the gas that was trapped inside the syringe. The students were able to read the volume from the video images that show the syringe and the pressure by making two readings on a manometer. Supplementary instructions written in the Laboratory Manual advised student to collect at least four measurements, including those with the lowest and the highest pressure. After measurements were made students were directed to the tabulated data and asked to choose x and y variables to plot the pressure – volume and the pressure – inverse volume relationships. Finally, once the relationship was shown on screen, students were asked to interpret the graphically derived $p - 1/V$ relationship. Figure 6.1. shows the capture of the screen showing the apparatus and the type of interaction that was provided to students during the task. This task was given to the students during the laboratory class that addressed gases (Molar volume of gases) with no practical experiment for the Boyle's Law.

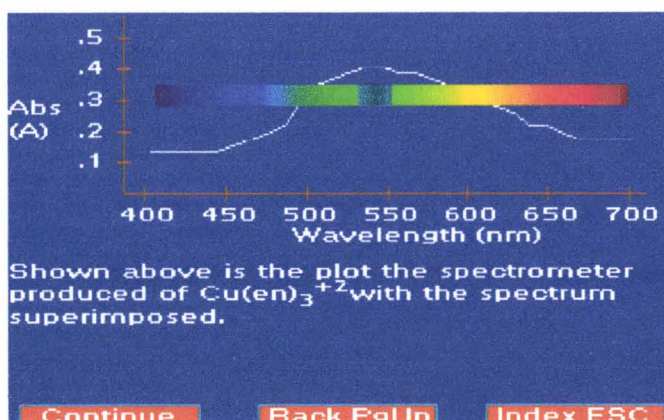
Task 2: A tutorial on colours and absorption spectra (Smith, Jones & Gammon, 1992) - Students matched the absorption spectra of solutions to the visible spectrum of light in order to develop an understanding of complementary colours in a tutorial that supplemented the laboratory session. Students were directed through a set of screens. At the start of the experiment, students were introduced to the colours in the visible spectrum and this was followed by a simple example aimed to clarify the relationship between the wavelength of the absorbed light and the colour being absorbed. The next set of screens aimed to relate the colour (and wavelength) of the absorbed light and the colour that we see (the transmitted part of the visible spectrum). Finally, students were given different transition metal complexes and were asked to relate the colour of the

compound to the nature of the ligands coordinated around the transition metal ion. This task was given to the students during the laboratory class that addressed transition metal ion complexes to complement the laboratory experiment. Figure 6.2. shows the capture of one screen in Task 2 and the type of controls that allowed for interaction by the students.



Smith, Jones and Common, 1992

Figure 6.1. One of the screens in Task 1, showing the apparatus for the simulated measurements of the relationship between pressure and volume and the type of controls that allowed for interaction with students.



Smith, Jones and Common, 1992

Figure 6.2. One of the screens in Task 2, showing the absorbance plot for the Cu(en)_3^{2+} ion, together with the superimposed band of colours from the visible spectrum. The type of controls that allowed for interaction by the students is also shown.

Task 3: A problem solving exercise on molecular geometry (Lower, 1992) - This was a quiz-style tutorial in which students analysed a series of compounds in terms of

valence electron pairs and predicted the molecular geometry. The exercise consisted of ten randomly chosen problems on inorganic compounds or ions. In order to solve each problem, students were led through three steps. In the first step students were asked to enter the number of bonding and the number of lone pairs of electrons on the central atom. In the next step they were asked to click on the appropriate shape. The last step informed students if they had solved the problem correctly or not and offered the right solution. The same steps were repeated for all problems. This task was recommended to the students as a part of assignment that addressed fundamental chemistry concepts (Unit1, Part 1 – The structure of atoms and Lewis diagrams and Part 2 – Shapes of molecules; VSEPR Theory).

Click on the appropriate shape

- linear
- bent
- trigonal
- tetrahedral
- square planar
- trig pyramid
- square pyramid
- trig bipyramid
- pent bipyramid
- T-shape
- octahedral
- see-saw

What is the **shape** of this molecule?

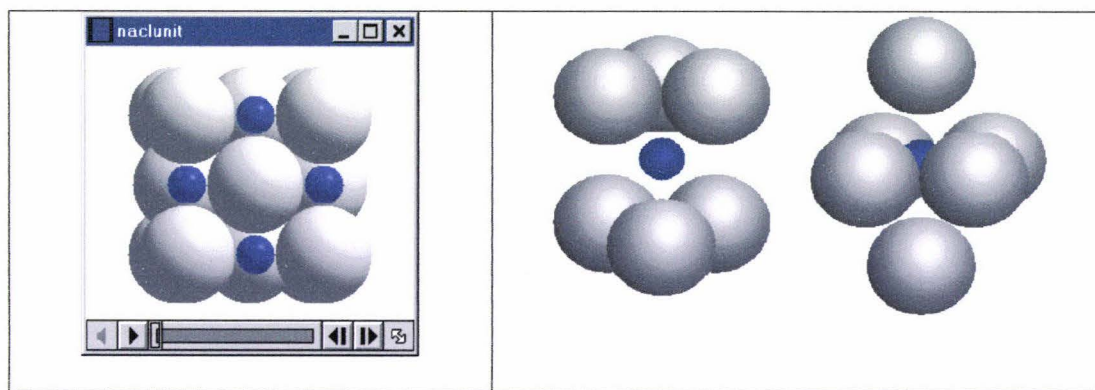
problem 1 of 10

molecule name:
chlorine trifluoride
formula: **ClF3**

number of bonding pairs = 3
number of lone pairs = 2

Figure 6.3. One of the screens in Task 3, showing the kind of questions and the type of controls that allowed for interaction with the students.

Task 4: A tutorial in which students use 3D animations of unit cells (Lisensky & Ellis, 1995) to supplement a laboratory session on solid-state structures - Students used 3D animations of unit cells of solids to answer questions about cavities in solids and the characteristics of unit cells. Students were instructed to do this exercise during a laboratory class that explored the three-dimensional structures of solids. The viewing of the animations was aimed at clarifying concepts of the types of cavities inside three-dimensional structures and the three-dimensional unit cells of ionic solids. Furthermore, viewing the animations provided the students with the opportunity to answer the required questions in their Laboratory Manual.



Lisensky & Ellis, 1995

Figure 6.4. The capture of two screens of video clips in Task 4, left showing the unit cell of NaCl and right showing octahedral cavity in the same structure. The computer generated animations were available to students as a supplement to the laboratory session on solid-state structures.

Three tasks formed part of laboratory classes (Task 1, Task 2 and Task 4) and one was an optional tutorial exercise (Task 3).

6.2.2. Students and Sampling

About 300 students who either planned to advance in chemistry, or were taking subjects that require a basic tertiary-level grounding in chemistry, took this paper.

An overview of student participation in the four different tasks is given in Table 6.2. Thirty-one volunteers participated in the study, with twelve students performing Task 1, eleven in Task 2, six participated in Task 3 and eight in Task 4. Three students participated in more than one task. Two female students participated in three tasks, in one task working individually, in two tasks working in a pair. One male student participated twice working as an individual. A total of 32 interviews was conducted.

Participant Selection for the Laboratory-Based Tasks (Task 1, Task 2 and Task 4)

In the Chemistry I(b) course, the students were grouped into different laboratory streams (depending on the papers in which they were enrolled) and attended one three-hour laboratory class per week. As the number of computers available in the adjacent computer room was less than the number of students in each laboratory stream, it was suggested that students do the computer part of the laboratory experiment in pairs. However, some of the participants in this study preferred to work individually (at their “own pace”), and in one case three students expressed an interest in forming a group. Ultimately, the choice of working in groups or individually was left up to the students.

For the study, one computer was moved from the computer room into an adjacent empty laboratory containing the apparatus needed to video record the task performance and the stimulated recall interviewing, which took place immediately after the task performance.

Participant Selection for the Assignment, Task 3

In the Chemistry 1(b) course the students were given weekly assignments to help them review the concepts addressed during the week. One of the assignments suggested students to perform the computer-based Task 3. Although strongly recommended to all students, it was an optional task. Volunteers from the lecture classes were invited to participate in Task 3. Students willing to participate in the study contacted the researcher and a time was set for the study.

As described in Chapter 5, section 5.2.1. the method of sample selection described above is probably best described as "purposeful" (Merriam, 1998; Mertens, 1998). The insights into the use of computers in learning undergraduate chemistry can be most effectively gained from a sample of chemistry undergraduates interacting with the chemistry software at the appropriate time in their course.

Table 6.2. Student participation in the four different tasks (Study One).

Task/No. of participants	Student proportion				Stimulated recall interviews
	No.	%	Individ.	Group	
1. Simulated Boyle's Law Experiment /12	7F 5M	58 42	1F,1M	2F,1M, 2FM	10
2. Colours and Absorbance Supplementary Tutorial /11	7F 4M	64 46	2M	2F,1FM, 1FFM ^a	8 ^b
3. Molecular Shape Tutorial-VSEPR Theory /6	3F 3M	50 50	2M,2F	1FM	6
4. Three Dimensional Structures Animations /8	3F 5M	38 62	0	1F,2M, 1FM	8 ^b

^a Three-member group

^b Brief interviews only after the exercise

M=male, F=female, FM=mixed gender

6.2.3. Techniques in Data Collection

The following techniques were used:

(a) Stimulated recall interviews (described in Chapter 5), involved semi-structured

interviews, task performance observation and the writing of field notes.

In order to become familiar with the technique and to make sure the technique gave high quality data, pilot stimulated recall interviews were first carried out with a range of CAI tasks. From this preliminary round of interviews, the four tasks described above were selected for inclusion in the study. Participants who performed Task 1, Task 2 and Task 4 were videotaped during the regular laboratory class.

Semi-structured interviews using the videos to stimulate recall were held immediately after the task performance. Because of the restricted time during the laboratory classes, brief interviews (20 min. to half an hour) were held after Task 2 and Task 4 performance. Interviews held after the performance of Task 1 or Task 3 lasted from 30 to 45 minutes.

At the beginning open-ended general questions were asked such as "How would you describe this exercise? How familiar are you with the computer use?"

As the task performance took place, the researcher observed the mixed split-screen tape showing both the student and the computer-screen indicating student responses to the task. This observation allowed the researcher to make field notes as the task performance took place and to highlight points of interest for later questions. Because the student was observing the same tape during the stimulated recall interviewing, if the student did not clarify a point highlighted in the field notes, the researcher could ask questions such as "What were you thinking here? What made you choose this solution? How did you go about this information/question/diagram?" The aspects that were recorded in field notes were also used later in the analysis process.

Although the technique of stimulated recall interviewing is described in the literature (O'Brien, 1993), the application of the technique such as used in the study was not reported earlier.

(b) Student laboratory report (document) analysis. Task 1, Task 2 and Task 4 were part of regular laboratory classes and student laboratory reports were used as additional data. Writing laboratory reports was compulsory for all students on completion of each laboratory class. The students' laboratory reports contained answers to questions relating to the tasks described in this study.

Other data such as course test results were also collected and used to check that the representative sample of participants ranged from A-grade students to those who failed

the course test.

6.2.4. Coding of Data

Each piece of data was coded using the student's pseudonym, the date, the task title and the information if the task was performed individually or working in a group (see Appendix 2 for examples of each type of data). For the students who participated in more than one task, pseudonyms were kept the same.

After the coding, all videotapes of the task performance and the subsequent interviews were transcribed by the researcher. The transcripts of any student-student conversation during the task performance (in the cases where students worked in groups) were combined with the interview transcripts (both the transcripts of the student-student conversation and of the interview are given in Appendix 2).

Non-verbal data from the videotapes were added to the transcription in the form of annotations (red font letters were used for annotations in the transcripts given in Appendix 2)

Copies of the student laboratory reports were added to each transcript when appropriate. A set of data that includes a list of the participants in Study One, an interview transcript, a transcript of student-student conversation accompanied with a copy of the laboratory report is given in Appendix 2.

6.2.5. Data Analysis

The analysis of the data involved a process that Merriam (1998, pp. 180-182) described as a step-by-step process.

(i) Step-by-Step Process

Step 1 – Forming the lists of items for individual set of data

The analysis started with the reading of the first interview transcript, while replaying the tapes of both the task performance and the stimulated interview and looking at the field notes and the student's laboratory report for each task. During the process notes of comments and terms that emerged from the data were made.

Analysis of the first set of data relating to Task 1 resulted in a preliminary list of items

as shown in Table 6.3. Data source was given for each listed item. It is noteworthy that only a few listed items were derived from the student discourse (interview transcripts) alone. In most cases multiple sources were used. In some cases insights, which were identified as important in describing student–task interactions, emerged from observing the videotapes and were not found in transcripts of student discourse.

The value of observing video-tapes is not only in providing confirmation of the insights already discovered in the student discourse from the transcripts, but also in revealing the insights that might stay hidden in the transcripts only (e.g. the ways students receive the on-screen information). This is particularly important in qualitative analysis of student use of computers in which quite often words cannot describe all kinds of student engagements involved in student-software interaction. Student laboratory reports were used as an additional support to already identified items.

The same analytical process was repeated with the next set of data. Table 6.4. shows a list of items after the analysis of the second set of data (Task 1).

A list of items of the second set of data for Task 1 is included in Table 6.4. because it illustrates the difference in the amount of data available when tasks were performed by pairs of students. Apart from the amount of data, data collected from students working in pairs when compared with the data collected from participants working individually differed in the quality as well.

In addition to other data sources, when students worked in pairs, student discourse from the student-student conversation was always found to be valuable. Not only did this data source confirm the insights found elsewhere, but sometimes also revealed new insights. An example of the use of student-student conversation from this set of data (students struggling to reach the understanding of pressure of 760 mm Hg) will be given together with examples taken from other tasks, later in the section in which the results are discussed.

Table 6.3. Preliminary list of items from the analysis of one set of Task 1 data.

Task 1 – p-V Experiment (Set of data for Bill)	
Item (terms/comments/notes)	Data source
1. Experience in computer use – good – “I am good with computers”.	student discourse (interview transcript)
2. Prior knowledge of gas laws/confidence - very good, parallel course in Physics - “.. too simple, easy ..”	student discourse (interview transcript), observing the task performance (video-tape)
3. Simulation vs. real experiment – preference for simulations - “You are not doing large errors”	student discourse (interview transcript)
4. Navigation through task - good, used link Back on the screen (after reaching U-tube; in discussion after clicking T-p instead of p-V experiment)	observing the task performance (video-tape)
5. Apparatus – manipulation, understanding how it works – clearly understood - “.. knew what I was doing”..)	student discourse (interview transcript), observing the task performance (video-tape)
6. Results – recording – not enough measurements were recorded, three instead of four	observing the task performance (video-tape), student’s laboratory report
7. Calculation involved - clearly understood (no problems observed or discussed)	observing the task performance (video-tape), student discourse (interview transcript)
8. p - V relationship and graphical interpretation – clearly understood (no problems observed or discussed)	student discourse (interview transcript), observing the task performance (video-tape), student’s laboratory report
9. Control of variables – clearly understood (no problems observed or discussed)	student discourse (interview transcript)
10. Ability to notice the on-screen information – moderate, clicked title T-p instead of p –V	observing the task performance (video-tape)
11. Satisfaction with the task - poor , “.. too simple, .. not challenging at all” (for his learning needs)	student discourse (interview transcript)
12. Omissions in the task – the task did not offer a challenge for different learning needs	observing the task performance (video-tape), student discourse (interview transcript)
13. Instructions from Lab manual - not followed	observing the task performance (video-tape)

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Table 6.4. List of items found in another set of Task 1 data.

Task 1 – <i>p-V</i> Experiment (Set of data for Donna – Donna and Casey)	
Item (terms/comments/notes)	Instrument source
1. Experience in computer use – moderate (some experience but not confidence) – “Ok, I use them in chemistry course”.	student discourse (interview transcript)
2. Prior knowledge of the concept - gas laws/confidence – experience from 7th Form but “You have to understand to go any further”	student discourse (interview transcript), observing the task performance (video-tape)
3. Simulation vs. real experiment – preference for real experiment - “not as comfortable as if you can set it up on your own”	student discourse (interview transcript)
4. Navigation through task – moderate - “ <i>Can we go back?</i> ” – started the task again to reach the missed answers	observing the task performance (video-tape), student discourse (transcript of student-student conversation)
5. Apparatus – manipulation, understanding how it works – not clearly understood “I don’t quite understand which .. parts are going to measure ..”	student discourse (interview transcript), observing the task performance (video-tape), student discourse (transcript of student - student conversation)
6. Results – recording – good (no problems observed)	observing the task performance (video-tape), student’s laboratory report
7. Calculation involved - confused with the calculation of pressure – “Is the minus on the right or left side of the U-tube?”	observing the task performance and the interview in which body language - hands were involved (video-tapes), student discourse (interview transcript)
8. <i>p-V</i> relationship and graphical interpretation – moderate - “.. because it didn’t come up the straight line .. it actually has to be straighter”	student discourse (transcript of student-student conversation), observing the task performance (video-tape), student’s laboratory report
9. Control of variables – problems in understanding that not only T but also <i>n</i> of gas was kept constant	student discourse (transcript of student-student conversation and interview transcript)
10. Pressure of 760 mmHg – understanding not achieved – answer in lab report “Where does the 760 come from?”	student discourse (transcript of student-student conversation and interview transcript), student’s laboratory report
11. Ability to notice the on-screen information and use it later – an information that <i>n</i> was kept constant appeared twice on screen, but was not being noticed, even at a time they restarted the task in order to find that answer	student discourse (transcript of student-student conversation and interview transcript), observing the task performance (video-tape)
12. Satisfaction with the task – good -“was good”	student discourse (interview transcript), observing the task

	performance (video-tape)
13. Omissions in the task -“no explanation for 760 mm Hg, it keeps turning up”, does not match the course requirements - in the course the unit used for pressure in kPa; no link to theoretical background “.. adding the one side of the tube minus the other side, but not saying why one was taking from the other, like just pick one side minus from the other side “ or “How could we know that the gas is an ideal gas?”	observing the task performance (video-tape), student discourse (transcript of student-student conversation and interview transcript)
14. Instructions from Lab manual – followed (recorded four measurements as was instructed; read aloud and tried to answer all questions from the Lab manual)	Student discourse (transcript of student-student conversation), observing the task performance (video-tape), student’s laboratory report
15. Student–student interaction – good (rich discussion during the task, cooperation in trying to clarify unknowns)	Student discourse (transcript of student-student conversation and interview transcript), observing the task performance (video-tape)

Step 2 –Identification of themes

The list of items from the second set of data was compared to the listed items made from the first set of data. The two lists were merged to allow some patterns to develop. The following findings were found:

- Most of the items that appeared on two lists were the same, although with different student responses (see for example student responses to simulation versus real experiment). Individuals differed in for example their familiarity in computer use or in their prior knowledge of the chemistry concept addressed (Bill was doing university physics as a parallel course, while Donna had 7th form chemistry background).
- However, there were items specific for the second list only. For example, an item of 760 mm Hg pressure became apparent in the analysis of the second set of data. That issue was specific for those students and was not found in the first list of items. Once the two lists were merged this item was kept for the further analysis.

After all sets of data related to Task 1 were completed, the analysis resulted in the final list of items related to Task 1.

The procedure was repeated for all different tasks. Table 6.5. shows the final list of items for four different tasks. Individual students’ responses and the data sources are omitted.

Table 6.5. Final list of items for different tasks.

Final list of items /regularities for different tasks			
Task 1 Boyle's Law (p-V) Simulated Experiment	Task 2 Light Absorption Tutorial	Task 3 Molecular Shape Tutorial	Task 4 Solid State Structures
Experience in computer use	Experience in computer use	Experience in computer use	Experience in computer use
Prior knowledge of the concept - gas laws/confidence	Prior knowledge of the concept	Prior knowledge of the concept	Prior knowledge of the concept
Simulation vs. real experiment	Supplement to lab. experiment	Problem solving exercise	Video clips vs. pre-build models
Navigation through task	Navigation through task	Navigation through task	Navigation
Apparatus – manipulation, understanding how it works	Spectrum of white light	Valence electrons around the central atom	Type and sizes of cavities
Results – recording	Spectrum of water	Bonding/lone pairs	
Calculation	Colour absorbed and corresponding wavelength	Identifying/ Familiarity with shapes (seesaw)	Unit cells of ionic solids-diatomic
p-V relationship and graphical interpretation	Colour absorbed by solution vs. appearing colour of solution/prediction	Regular /Distortion of regular shape /molecular geometry	Unit cells of ionic solids – binary compounds
Control of variables	Wavelength -energy of light relationship	Terminology	Terminology - cavities (Lab. manual) vs. holes (video clips)
Pressure of 760 mmHg	Ligand field splitting – colour of complex (E of light – field splitting relationship)		
Ability to notice the on-screen information and use it later	Ability to notice the on-screen information (black band over spectrum)	Ability to deal with the on-screen instruction	Ability to notice the on-screen information
Instructions from Lab manual	Instructions from Lab manual	Guessing	Instructions from Lab manual / running the videos
Satisfaction with the task	Satisfaction with the task	Satisfaction with the task	Satisfaction with the task
Student-student interaction (for students working in groups)	Student-student interaction (for students working in groups)	Student-student interaction (for students working in groups)	Student-student interaction (for students working in groups)

Feedback	Feedback	Feedback /running score	
Omissions in the task (problems in navigation through task; problems in providing an information for individual needs)	Omissions in the task (problems in navigation through task; wrong coloured solution in beaker), no explanation for ligand 'en'	Omissions in the task (error in the one problem; all screens from one problem should contain the formula	

Once the final lists of items for all tasks were formed, the process moved on and the patterns of regularities became apparent. Different listed items were sorted and named to different groups of items.

All items that were specific to the concepts addressed by the particular task were sorted in one group of items and named **concept related items** (for example in Task 1 student responses such as discussion of p - V relationship or discussion about pressure of 760 mm Hg). Concept related items were different for different tasks.

Another group of items was named **software related items** and contained items related to the design of the particular task (navigation, simulation type of software application in Task 1 or problem solving exercise in Task 3, etc.). Some of the software related items were common for all tasks (for example navigation through task), while others differed for different tasks (Task 1 – simulated experiment, Task 3 – problem solving exercise).

The third group of items included those that derived as a consequence of individual differences between the students and was named **student characteristics related items** (different prior knowledge, familiarity with computer use etc.). Most of the items in this group were common to all tasks.

When all the grouped lists of items derived for all four different tasks were reanalysed, two distinctive forms of organised descriptive themes became apparent. The first theme (Theme One) referred to the student interaction with the chemistry concept addressed by that particular task or software. The items grouped in this theme were concept specific and they differed for each different task.

The second theme (Theme Two) referred to items collected from a particular student – software interaction that was not specific just for that particular task but informed about a more general understanding of student interaction with software applications. Both

the student characteristics related items and the software related items contributed to this theme and informed about student interaction with different types of software.

Table 6.6. shows the themes that emerged after items of all sets of data and from all tasks were combined. Furthermore the identified themes were aimed to reflect the purpose of the study (the research questions) in the way that the researcher had discovered in the data during the analysis process.

Having identified the themes for the analysis in the step of analysis that follows, the data were re-evaluated to uncover developing conclusions.

Table 6.6. The emerged themes resulted from the step of analysis in which the items of all sets of data and from all tasks were combined.

Theme	Description
Theme One Items that inform about student interaction with the particular task - concept related items	Specific to task and includes chemistry concept related items. For different tasks the items were different as different tasks addressed different concepts in chemistry (for example for Task 1: p-V relationship and graphical interpretation; apparatus – manipulation, how it works; pressure of 760 mm Hg; control of variables etc.)
Theme Two Items that inform about student - software interaction more general	Although some of the items might have derived from the student-software interaction with only one task, they might inform generally about the student-software interaction. The student characteristics related items and the software related items that are of significance for the student use of chemistry software were placed in this theme. <i>Items that relate to student characteristics</i> involve student prior knowledge; familiarity with the computer use; student-student interaction (when working in groups), student experience of the computer-based application such as preference for simulation/real experiment; student ability to register the on-screen information and use it later on; student use of the complementing lab manual instructions; satisfaction with the task. <i>Software related items</i> involve a type of software application – simulation/a replacement for a real experiment (Task 1), tutorial type (Task 2), problem solving type (Task3), video clips (Task 4); navigation through task; feedback – the same feedback (nonadaptive) regardless of the student response, feedback in a form of running score (Task 3); omissions to provide the student information he/she needed.

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Step 3 – Data analysis by Theme One – Learning objectives and student achievement of intended learning outcomes

After identifying the major themes, each theme was taken in turn and the data appropriate to that theme separated. To provide a structure for the analysis that allows

conclusions further steps were developed appropriate to the particular data sets.

In the case of the theme related to chemistry concepts, the data were already classified by the four different tasks. Each item was reanalysed in terms of the learning objectives associated with each task to give a measure of the level of achievement of the intended learning outcomes by the student.

Where possible the target objectives were taken from those already set up either by the laboratory experiment or by the software program. Task 1, Task 2 and Task 4 were part of laboratory classes and the objectives were given in the Laboratory Manual (see Appendix 3, CD ROM Appendices for the copies of these experiments from the Laboratory Manual, 1997). For Task 3 the learning objectives were not explicit and had to be deduced from the software program by careful examination of the steps required in the task (an outline of the steps for Task 3 were given in Section 6.2.1.).

An independent check of the intended learning objectives was made by the course co-ordinator. The objectives for four different tasks are listed in Table 6.7.

Table 6.7. Formulated target objectives for different tasks.

Task	Target Learning Objectives
Task 1 Boyle's Law Experiment	• Use the equipment (to obtain measurements) • Explain how the equipment works (understand movement of Hg level in U tube and calculation of the pressure of a gas trapped) • Describe the pressure-volume relationship of gases • Interpret graphs • Control variables in the experiment
Task 2 Light Absorption Tutorial	• The relationship between the colour of complexes and absorbed light • Use absorption spectra to predict the colour of complexes • Relate the effect of ligand change on the colour of a complex
Task 3 Molecular Shape Tutorial	• Identify the valence electrons around the central atom, as bonding pairs or lone pairs • The structural consequences of the number of electron pairs • The distortion of regular molecular geometry caused by lone pairs
Task 4 Solid State Structures	• Identify the types and sizes of cavities present in 3D arrangements of atoms • Identify the constitution of unit cells of binary 1:1 ionic solids • Identify the constitution of unit cells of binary 1:2 ionic solids

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Each item assigned to Theme One from the group - *concept related items* (for concept related items of Task 1 see Table 6.6.) was compared to the listed target objectives. For example, in Task 1 an item *p-V relationship and graphical interpretation* (Table 6.5.) was targeted by two objectives for Task 1 *Describe the pressure-volume relationship of gases* and *Interpret graphs* (Table 6.7.)

Most of the concept related items listed in Table 6.6. were classified as those targeted by the task objectives. For example, the concept related items for Task 1 apparatus – manipulation, how it works, were matched by the two target objectives for Task 1 - Use the equipment (to obtain measurements) and Explain how the equipment works (understand movement of Hg level in U tube and calculation of the pressure of a gas trapped) (Table 6.7.). However, there were concept related items such as ‘atmospheric pressure of 760 mm Hg’ in Task 1 that were not set up as an objective to be learnt by doing the task. It was assumed (by both the software developers and the course coordinator who had not provided the students with the information about the atmospheric pressure of 760 mm Hg either in the software or in laboratory manual implemented instruction) that the knowledge about atmospheric pressure of 760 mm Hg should be part of student prior knowledge before commencing the task. Hence, this item informed about students’ prior knowledge, which was classified in Theme Two – student characteristics related item.

From the classification of items and formulation of task objectives, the analysis moved forward and the individual student responses to each listed item were considered (those were omitted in Steps 2-3). Those were taken from the individual lists made in Step 1 of the analysis, which indicated student’s responses to each item. Data, which included student discourse from the transcripts, on-screen evidence and student answers to the question in student laboratory report, all related to the selected item, were checked again in order to evaluate how well the particular objective was achieved by the individual participant.

The same procedure for the same selected item was repeated for each individual student and also repeated for each content-related item for each task. Once the target objectives were formulated for each task and the individual student responses for each item were separated, it was possible to look at the individual student responses and seek evidence that indicated how well the student achieved those target objectives.

Consequently, Theme One, that was identified in the previous step of the analysis and initially represented by the particular task/concept related items, gradually evolved into what was the aim of the final step of analysis evaluation of how well students achieved target objectives or the theme named - *Student achievement of intended learning outcomes.*

Step 4 - Data analysis by Theme Two - Factors that affected student achievement of intended learning outcomes

Theme Two (see Table 6.6.), referred to student interactions with the different software applications. A survey of the data showed that items related to student characteristics and items related to the software both influenced students' performance on the task and hence their achievements of task objectives.

The aim of the analysis described in Step 3 was to evaluate the student achievement for each of the task objectives. The *items related to student characteristics* and *software related items* from Theme Two both affected the student achievement. It is, of course, possible to think of a range of other factors that would also be expected to contribute to student achievement of intended learning outcomes (such as student approaches to learning, factors related to student three-dimensional ability, motivation, ethnic background, social background etc.) but these could not be inferred from the data described in this thesis and therefore have not been considered here.

Therefore, a theme called ***Factors that affected student achievement of intended learning outcomes*** evolved from Theme Two with two sub-themes, one related to individual student characteristics and the other to software design (see Table 6.6.).

Dimensions of the sub-theme related to the student characteristics that influenced student-task interaction and student achievement of the task objectives (prior knowledge about a topic addressed by the task, interaction with other students if working in group, familiarity with computers in general and satisfaction with the particular task or software application) contributed to all tasks. Dimensions of the sub-theme related to the software design that influenced student-task interaction and student achievement of the task objectives (different types of software application, feedback, use of guessing, errors and omissions in the software and implementing instructions) differed from task to task. The items for each sub-theme are listed for Theme Two in Table 6.6. in Step 2 of the analysis described earlier.

Individual lists that were made in Step 1 included individual student responses related to each listed item. These student responses were initially used prior to the final judgement in which the three-point scale classification of student responses was employed.

A reviewing of the tapes and rereading of transcripts then took place to confirm that all

the items, both those referring to student characteristics and those related to different software applications, were addressed and that the individual student's responses are recorded.

Step 5 – Evaluation of student-task interaction

Both the evaluation of student achievement of task objectives (intended learning outcomes) and the evaluation of how different factors affected student achievement of intended learning outcomes contributed to the Evaluation of student-task interaction.

Although the analysis led to the classification into two themes, in getting insights into student – task interaction, both themes with the contributing items were interwoven.

For example, a concept related item mentioned earlier – atmospheric pressure of 760 mm Hg in Task 1 - was not listed as an objective to be learnt. It was not included either in the aim or in questions related to the part of laboratory class in which the Task 1 was used. Therefore, both the task designers and the laboratory course coordinator assumed that understanding of atmospheric pressure of 760 mm Hg is to be brought as student prior knowledge before commencing the task (no explanation in the software was given for atmospheric pressure of 760 mm Hg, and no explanation of atmospheric pressure of 760 mm Hg was given in Laboratory manual instruction for this part of experiment; also in the course 101.32 kPa is used for normal atmospheric pressure). Therefore, some of the concept related items from Theme One informed about the student prior knowledge, a student characteristics related dimension of Theme Two. At the same time, the same item also informed about a software related dimension - the omissions of the software which did not provide the student the information she/he needed.

For that reason, in the discussion of the results, one student quote given to support one insight can easily be used to indicate other insights as well.

In describing findings of this study, an attempt was made to include the quotes of as many participants as possible, and for as many different task objectives (and from different tasks) as possible. However, there were some limitations.

The first limitation refers to the participants themselves. Some participants talked more readily than others. Furthermore, for the selective objectives, some student descriptions were richer than others. Some participants and particularly those who volunteered in more than one task enjoyed being able to talk about their experiences. The utterances of the participants who were short in their descriptions were omitted if they did not add

any new insight to those already identified. For that reason, in the section showing the results (6.3. Results) the quotes of some participants appear more frequently, while the quotes of others are not included.

The second limitation refers to the nature of the particular task. Task 4 was part of regular laboratory class, but differed from the other tasks. It contained a set of video-clips to help students in understanding the complex nature of the structure of solids. No additional on-screen interaction was provided to students, except instructions to run the video clip by clicking on the sign “x”. Students were asked to answer the supplementary questions given in the Laboratory manual book. Furthermore, this laboratory class was very busy and only very short interviews were performed during the regular laboratory class. The nature of the concept being addressed and the time limited for the interviews resulted in very short student answers with generally poor descriptions. A more detailed analysis of student interaction with this type of software and particularly the student understanding of the topic addressed in Task 4 was left as a target for a future analysis. Although the same analysis has been done for this task, for the reasons given above, student quotes from this task do not appear as often as from other tasks. In most cases, the already identified insights supported by the rich description given by the participants in other tasks, were confirmed by the less rich description of the participants in Task 4.

Evaluation of student achievement of intended learning outcomes

The evaluation of student achievement of target objectives was done for each task and for each of the participants and took place in two stages.

In the first stage in the evaluation of student achievement, the levels of student achievement were classified on a three-point scale, good, moderate or poor.

Criteria for evaluation involved the analysis of how different tasks influenced both students’ cognitive (what they learnt) and affective (how they felt) dimensions. An agreement of a student’s explanation for a given concept with the formal, scientific explanation was considered as cognitive dimension, with a level of student satisfaction with a particular task that contributed as an affective dimension (body language). For good achievement a detailed description and an agreement of student explanation and the formal scientific explanation were found. Often, good achievement was supported with student satisfaction. For moderate achievement students were able to recall some brief scientific definitions (partial agreement), but short answers did not provide the

evidence that the learning objective was achieved. Very poor student discourse and no agreement with the formal scientific explanation of the concept were evaluated as not achieved.

The three-point scale evaluation was deduced from the student discourse, observation of the tapes and the researcher's notes (see Table 6.2. with the list of items extracted during the analysis of one set of data related to Task1).

In the second stage of evaluation of student achievement, all students' responses to individual task objectives (verbal and nonverbal) were classified as achieved or not achieved. For a level of achievement evaluated as achieved, an explanation given during the interview that agreed with the scientific formal explanation for the particular task objective was evident (supported by student discourse, videotape record and/or student's laboratory report). Some participants had taken an opportunity to go page back (the option was available from some screens in Task 1 and Task 2 respectively) to check the question and their reasoning before the learning outcome was achieved. For level of achievement evaluated as not achieved, only partial or no agreement with the scientific formal explanation was found in data (student's discourse, videotapes and student's report). The cases in which the evidence was not clear in data were labelled 'not evaluated'.

As stated previously for some task objectives the classification of achievement was distinguished using the student discourse only (for example, Task 1 – Explain how the equipment works). For other objectives, the main evidence for evaluation was sought in the transcript of student-student conversation, but also in the videotape records or in the student's laboratory report (for example, Task1 – Describe the pressure-volume relationship of gases). Although the evidence written in the form of an answer in the laboratory report was used as additional data source, for the evaluation of student achievement of some task objectives when the data from the main sources were unclear, this additional evidence was taken into account. Students' quotes usually informed of more than one factor and one quote can be used equally to support all of them. However, wherever possible the quotes were taken from different participants.

Some examples of the ways the evaluations of student achievement of intended learning outcomes was done are illustrated below. For example, in Task 1 for the objective **Use the equipment** (to obtain measurements), the evaluation of achievement was based upon the viewing of tapes (both of student-task performance and of stimulated recall

interviewing) supported by the student talk:

We knew actually how to use it, in the first part we actually got to see the movement, so you knew where the one side was and where the other side was .. (Rob)

On the other hand, the responses for the same task objective given by two other participants did not provide evidence that this task objective was achieved:

This one, it was harder [this participant volunteered in other tasks and compared this task with Task 2] because knowing how to use the apparatus, like, having this, sort of, set up .. if you are not familiar with the apparatus and with the concept it's hard.. you have to be aware of it before you do it, so you understand what's happening, yeah .. (Terry)

or

Uh, yeah, .. when the apparatus, equipment was set up I was not able to understand where it was present in front or back of the manometer. I wasn't able to get 3D picture. So, in that way I was a bit confused. ... But if I've seen that in the lab then I would know, .. I haven't done this experiment before. So, after I've seen this set up I just realised I don't know where they are actually connected .. (Vicky)

The quote of Vicky given above indicated her approach to simulations versus real laboratory experiments as well.

The next learning objective **Explain how the equipment works** (understand movement of Hg level in U tube and calculation of the pressure of a gas trapped) was more challenging because it required an understanding of a change in the mercury levels in both sides of manometer tube (change in pressure of a trapped gas) as a consequence of pushing in or pulling out the piston inside a syringe (change in volume of the gas). The calculation of the gas pressure was given in the software but required an understanding of why the atmospheric pressure of 760 mm was adjusted by the difference in mercury levels (reading on one side is added or subtracted from another).

This response from Bill was used as evidence that this learning objective was achieved:

.. seven sixty and .. if the right hand side is minus and the left hand side plus, then .. the difference between them is countable .. (Bill, from conversation between Bill and Vicky)

The response from Donna indicated that the objective was not achieved:

.. but it is also saying, like as, adding the one side of tube and minus the other, but not saying why one was taking from the other, like .. just, pick one side

minus the other eventually, one side is always minus from the other side, .. yeah .. (Donna)

The same criteria were applied in evaluation of achievement of all learning objectives and for all four different tasks. All tasks have the objectives that were identified as more challenging. The responses in which the evidence of achievement was not found or was not clear were not evaluated.

Evaluation of factors that affected student achievement of intended learning outcomes

The criteria of evaluation of how different factors affected student achievement of task objectives differed from one factor to another. Student prior knowledge was not evaluated using the pre-test (and post-test) form of evaluation (no intention was made to let the participants feel that their knowledge is tested and judged). Rather, during the interviewing students were asked of previous (high school) experiences about a concept addressed by the software tasks and their discourse only was used in evaluation. In addition to describing what they knew about a topic before commencing the task (from high school), data were gathered from other students' comments during the interview or from student-student conversation during the task performance (e.g. in Task 1 conversation between Donna and Casey about the 760 mm Hg atmospheric pressure, given later in results, section 6.3.2.).

Student discourse was used as primary data source for most factors. However, in some cases the videotape observation and students' laboratory reports were used to support the claim. Body language, recorded on videotape, always supported the verbal description in evaluation of affective factors (e.g. satisfaction), while the evidence of how students followed the implementing instructions (given either by the software task or in their laboratory manual) was found in videotape records, student-student conversation and student laboratory reports. In cases of working in groups, a note of who manipulated the mouse was recorded in field notes.

The naming and the scale used in evaluation depended on each dimension being investigated. Whenever possible, a three-point scale was used. Again, another researcher checked and confirmed the evaluation.

As was illustrated earlier, in many cases, the one and the same student's quote informed of more than one factor. The selected examples of students' quotes can be used for

evaluation of multiple dimensions or factors that affected student achievement of intended learning outcomes. For example, a description below:

I have no experience in that. I left after Sixth Form, so I didn't do Seventh Form at all [the final year of high school]. I didn't enjoy this one [Task 1]. I don't know the answers, you know ... like ... Um, it was not as enjoyable a subject ... I found it boring as well. I think we made ... We got everything wrong, didn't we? (Ali)

was used as evidence when assigning poor prior knowledge about a topic to the student in question for Task 1, negative student satisfaction with this task, and also that little learning had occurred after the task completion.

Some participants indicated their prior knowledge about a topic addressed by the task without prompting:

.. I don't think I got much from it [Task 1] because it didn't challenge me in any way. I mean, this, all the things we have either done on the lectures in chemistry or physics .. so .. (Bill)

Good prior knowledge was assigned to Bill. In other cases in which an indication of prior knowledge was not explicitly given, the evidence was sought out from the comments made on task demands during the stimulated recall interviewing. Examples from Task 2 show how the evaluation of student prior knowledge can be based upon student description of the phenomenon. For example, at the start of the interview Kevin mentioned:

.. I knew about colours and absorption .. (Kevin)

but did not clarify if that knowledge was gained from high school or from recent lectures at university. Kevin's explanation given later during the interview (see below) was used in evaluation of the more challenging learning objective - Relate the effect of ligand change on the colour of a complex. The same response was connected with what he had said earlier and was used in assigning good prior knowledge:

I know how the energy and the wavelength are related and how absorption depends on energy .. So, you can like predict what kind of ligands has got, what kind of colour compound can have .. (Kevin)

On the other hand, poor prior knowledge accompanied with the program design with inappropriate scaffolding help resulted in responses such as given from Leo:

I didn't know pretty much about this .. yeah, and ..
Was very hard to figure out the wavelength of the colours and the nanometers

of where the absorbance is and the colour .. the highest is to that end, or that end? ..so confusing, I had to read my book ..

I didn't get that right which way the energy is rating to colours, from shorter to wider and it's pretty tricky anyway .. the reason the colour that we see, because we lost the colour that it absorbs, just because it absorbs in the middle doesn't ... um, yeah .. it's hard, sort of, to figure it out..

It's red here [the computer screen shows the spectrum with the absorption peak in the red part of the visible spectrum and the red colour is blanked on the superimposed band] because it absorbs red, then must be violet, .. if absorbs violet must be red..

It doesn't seem as a good work, it takes time to figure it out anyway .. (Leo)

For some dimensions the process of evaluation was more straightforward. For example, during the interviewing students were asked about their familiarity with computers or their preference for simulation vs. real experiments (Task 1). Similarly in Task 4, in exploring three-dimensional structures of solids, students were asked to comment on the video clips compared to the pre-built concrete models that were available in the laboratory and for the interviewing purpose were placed beside the computer while the participants performed the task.

6.3. RESULTS

The aim of this study, which investigated the student interaction with each individual computer-based task, was to identify important features that describe or influence this interaction and to indicate possible solutions that can be implemented in improving the student – computer task interaction. For that reason, the results are treated together to provide an overview of the insights that derived from the student interaction with different types of chemistry software.

6.3.1. Student Achievement of Intended Learning Outcomes

The results of the classification of student achievement for learning objectives for each of the tasks are given in Table 6.8.

In view of the short nature of the tasks, and the preparation the students had received in lectures and tutorials prior to attempting the tasks, a high level of achievement was anticipated. However, the numbers in Table 6.8. show that roughly half of the students attempting the tasks failed to achieve the intended learning outcomes expected in the task. Analysis of the data showed that many students missed the point of, or failed to

grasp, important ideas canvassed in the tasks.

Table 6.8. Student achievement of task objectives.

Task and Objectives	Achievement/ No. of students' responses		
	achieved	not achie.	not eval.
Task 1. Boyle's Law Experiment (<i>12 participants</i>)			
• Use the equipment	6	6	0
• Explain how the equipment works	1	9	2
• Describe the pressure-volume relationship of gases	6	6	0
• Interpret graphs	6	4	2
• Control variables in the experiment	6	6	0
Total number of student achievements of each of the objectives	25	31	4
Task 2. Light Absorption Tutorial (<i>11 participants</i>)			
• Understand the relationship between the colour of complexes and absorbed light	5	6	0
• Use absorption spectra to predict the colour of complexes	5	6	0
• Relate the effect of ligand change on the colour of a complex	3	5	3
Total number of student achievements of each of the objectives	13	17	3
Task 3. Molecular Shape Tutorial (<i>6 participants</i>)			
• Identify the valence electrons around the central atom, as bonding pairs or lone pairs	2	4	0
• Understand the structural consequences of the number of electron pairs	1	5	0
• Understand the distortion of regular molecular geometry caused by lone pairs	1	5	0
Total number of student achievements of each of the objectives	4	14	0
Task 4. Solid State Structures (<i>8 participants</i>)			
• Identify the types and sizes of cavities present in 3D arrangements of atoms	8	0	0
• Identify the constitution of unit cells of binary 1:1 ionic solids	4	4	0
• Identify the constitution of unit cells of binary 1:2 ionic solids	2	6	0
Total number of student achievements of each of the objectives	14	10	0

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While all the students completed the tasks, there was often clear evidence that the achievement of some learning objectives had not been mastered. For example, while a larger number of the students were able to “use” the equipment in the simulated experiment in Task 1, analysis of the student performance clearly showed that most had difficulty achieving the objective of understanding how the virtual equipment they were manipulating would have worked.

R: How did you find the description of equipment?

Rob: Um, wasn't clear 'cause what they had there, 'cause they went through

the other parts, but they came to the electronic equipment here. You didn't know where it was, so you had to really look at it and see and understand what it had there.

R: So the amount of information you were given was not enough?

Rob: It didn't actually describe the electronic equipment. You saw everything else and understood that, but it added a few things here, where you shouldn't know what they worked ..

or

Terry: Should the piston be clamped? Um, ... I think, should the piston be clamped so it can't move.? Um, I think, I was thinking about that when I was getting confused.. They actually were clamped on the outside of it, hold in .. when I say should the piston be clamped I mean, I know that the piston is moving up and down [shows by her hands] but I was trying to visualise how could you clamp it, do you see what I mean, I was thinking how could you actually clamp it, I think I was more thinking about the clamp on the outside for some reason, yeah .. I don't know.

Student performance followed the pattern showing the poorer achievement for the more challenging objectives (e.g. Explain how the equipment works in Task 1; Relate the effect of ligand change on the colour of a complex in Task 2; Understand the distortion of regular molecular geometry caused by lone pairs in Task 3; Identify the constitution of unit cells of binary ionic solids in Task 4).

In the case of Task 3, student performance was particularly poor on the third objective (Understand the distortion of regular molecular geometry caused by lone pairs), which involved the use of more subtle aspects of valence shell electron pair repulsion theory (i.e. understanding that lone pairs require more room than bonding pairs and tend to compress the angles between the bonding pairs or understanding that the structure around a given atom is determined principally by minimising electron pair repulsions). While some students were able to construct knowledge from the information provided by the feedback, others needed further assistance which was not provided by the software.

The conversation between Paula and Jim during the Task 3 performance, and moving from problem 4 to solve problem 5 is an example of student engagement with the software in which the feedback provided and the peer cooperation resulted in construction of knowledge:

Problem 4/10 SF₄

Paula: So, there is five, but one is missing. So seesaw.

Jim: Are you sure?

Paula: Five is trigonal bipyramidal all right?, and you take
 Jim: I thought there was six stuff on it.
 [they seemed confused: 2 electrons, 1 lone pair, not two lone pairs!!]
 Paula: No, we've got five pairs this time, because one is just a lone pair on it
 and then is not bonded and so you take off from the equatorial..
 [she is moving her finger around the circle in equatorial positions]
 Jim: So, you've got five, you mean, .. bonding, yeah.
 Paula: Seesaw. Correct. You go down.

Problem 5/10 ClF_3

Paula: OK. That makes five. Five in total.
 Jim: If one goes to seesaw, that's T-shape.
 Paula: Yeah!
 [Jim didn't like to guess, wanted to do it by himself.]

On the other hand, Tim, who was familiar with computers, used guessing to a large extent and the help button as a way to overcome problems. He explains his attempts to find the number of lone pairs for the AlCl_3 , in shape determining exercise (Task 3).

It's point five, ..., so it's a half. So, I just thought, once I worked out what the program was, ... want to see what I can get away with ...
 I tried with negative number, so, there could only be one bigger after it. I need some help to find out what it is. I thought what, I thought what it should be. Computer said **no**. So, I had to find out at what area am I looking at... It [computer] told me what not to do ... (Tim)

Successfully completing the task did not mean that students had mastered the chemical ideas covered in the task. For example in Task 1, the simulated Boyle's Law experiment, while all students successfully obtained and graphed the data, the task did not probe the implications of graphs in terms of the properties of gases sufficiently to elicit understanding. The subsequent interviews and laboratory reports showed that many of the students had not mastered the ideas. Several students also expressed surprise as they finished this task, indicating that they were expecting more. Commonly, students were presented with a question, and an incorrect response provided information that allowed the student to change his/her response, but there was no subsequent check that understanding had been achieved.

6.3.2. Factors that Affected Student Achievement of Intended Learning Outcomes

Results of the theme *Factors that Affected Student Achievement of Intended Learning Outcomes* are presented for each of the identified sub-themes; the student

characteristics that influenced student-task interaction and student achievement of the task objectives, and the software design that influenced student-task interaction and student achievement of the task objectives.

(i) Insights into Student Characteristics that Affected Student Achievement of Intended Learning Outcomes

Table 6.9. shows the summary of student responses attributed to different dimensions of student characteristics that affected student achievement of the task objectives. Each of the dimensions (prior knowledge, student-student interaction, student-computer interaction and student satisfaction with each task) given in Table 6.9 is addressed separately below.

Table 6.9. Insights into student characteristics.

Insights	Task 1	Task 2	Task 3	Task 4
Prior knowledge				
good	2	3	1	0
moderate	1	7	1	6
poor	4	1	4	2
no data	5	0	0	0
Student-student interactions				
good	6	6	2	6
moderate	2	2	0	0
poor	2	1	0	2
Student-computer interaction				
good	7	5	3	2
moderate	2	4	1	0
poor	3	2	2	6
Satisfaction				
positive	5	8	4	4
neutral	6	3	1	3
negative	1	0	1	1

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(a) Prior Knowledge

In this study, students came to the task having been to lectures and after attending tutorials and laboratory exercises, but the data analysis revealed a wide range of background knowledge. Before the tasks were given to students either as parts of

laboratory classes or assignment the topics were introduced at lectures. However, their chemistry background prior to university differed (e.g. 7th Form Bursary Chemistry, 6th Form Chemistry, Catch-up course).

In Task 1 (simulated p - V experiment) expected prior knowledge before commencing Task 1 included having theoretical background in gas laws (including Boyle's Law), understanding of the properties of gases, using appropriate units and some abilities in solving problems. As in any other chemistry experiment students had to follow instruction and set up apparatus (was set up in the simulated experiment and the students had to understand it), they had to use the apparatus and do measurements, to record data, to represent the relationship between variables (plot graphs) and interpret data and results (e.g. graphical relationship).

For example, in Task 1, the conversation between students working in pairs revealed how one student struggled from the beginning to the end of the task performance with the meaning of the 760 mm Hg pressure. In their lectures the students were introduced to normal atmospheric pressure of 101.3 kPa and the alternative unit of 760 mm Hg level was unfamiliar to them. At the beginning:

Casey: So that the pressure pushes it up

Donna: I think .. so what do we need to measure [looks at the lab manual book] four data, at the highest possible and the lowest possible pressure [reads implementing instructions]

[now they read the computer screen which says: **pressure = 760 + 58 - 342 mm**]

Donna: so ... seven sixty ... minus ..

Casey: minus is the right arm

Donna: Where does seven sixty come from?

Casey: Um ... was at the start, wasn't it?

Later, during the next measurement:

[They are reading on the computer screen: **Right p = 760 + 348 - 52 = 1056 mm**]

Casey: Was it constant when we started?

Donna: Maybe, when the two of these get up to seven sixty

Casey: I don't know..

And again:

Donna: Shall we go to even?

Casey: OK.

Donna: 200, is it?

Casey: Yeah.

Donna: Add the right arm 200 minus the left 200 ... is seven sixty.

Casey: Hold up! Seven sixty. That must be when the arms are equal .. seven

sixty,

Students completed the task still not being able to clarify the meaning of atmospheric pressure of 760 mm Hg that kept appearing in the calculation of the pressure in the syringe. Later on, during the subsequent stimulated recall interviewing Donna addressed the issue on her own at the beginning of the interview:

Donna: Yeah, there was one thing. Seven sixty that is coming up at the equation, and we couldn't work out what that was ..

R: Will we come across that soon, you think? [tape is running]

Donna: .. yeah, there, we really didn't know where that seven sixty came from.

R: Right, so there is no explanation of the seven sixty?

Donna: No, keep turning up again and again, and we couldn't work out where it was coming from.

The example given above illustrates how the lack of student prior knowledge about the topic under investigation and the lack of task design to address it shadowed the student understanding of the task.

Two mature students took part in the study for Task 1 and both were uncertain of their mathematical ability and lacked experience manipulating experimental data graphically in Task 1. Both completed the exercise, but they displayed little understanding of the results.

At the other extreme, students having previous experience in the topic usually demonstrated the understanding expected. The interviews, however, showed that the task failed to meet the needs of these students by forcing them through a series of exercises that they found trivial and not providing tasks which challenged them. For example, in Task 1, some students were well prepared and found the task a useful, if slightly tedious, revision exercise.

Nina: Um, ... it's quite like as I remember in the Seventh Form how we did the experiment.

A different student, taking physics as a parallel course (a common subject choice), found the level of questioning inappropriately low and was also dissatisfied with the Task 1:

... some of the things are very simple .. really obvious.. some of the things ask the question like: Is this a straight line? .. It didn't challenge me in any way. I mean, these are all the things we either did in the lectures in chemistry or physics ... it doesn't help me learn if it says what is this, it's that. (Bill)

In a number of cases, the stimulated recall interviewing uncovered students' conceptions on topics addressed in the tasks. For example in Task 2 a number of students suggested that the colour of the compound was "opposite" to the colour of the absorbed light. This is a simplification of the concept that the colour of a compound is complementary to the colour of the absorbed light. The deficiency of the simplification was revealed when the task presented students with a purple compound and absorption of the yellow-green region of the spectrum leaving the colour derived from both red and the blue light.

(b) Student-Student Interactions

Students usually interacted well when working in pairs and the task provided the students with useful practice verbalising the chemical concepts. This was seen as computer assistance in peer tutoring. In Task 3, the problems on molecular shape forced students to use the chemical terms associated with VSEPR theory, and exchanges between students showed the clarification and refinement of students' use of terms during the task. For example, Jim thought (correctly) that the proper shape name for BF_3 should be "trigonal planar", not just "trigonal" even though Paula contradicted him.

Jim: If it's got no lone pairs it has to be planar.

Paula: Yeah. Well, that is what it does. It's trigonal!

Jim: Doesn't have to be planar?

Paula: No.

The subsequent interview showed that he was not totally convinced by Paula's argument.

In the study some pairs worked well to mutual benefit, but in other cases one student put in most of the effort and dominated the task.

For students performing a task in groups, good student-student interaction assumes the communication in which no domination or pushing is observed and enough time is left for individual group members to clarify ideas by repetition (as many times as they needed) until reaching a solution or gaining an understanding. One such example was identified in the conversation between Terry and Ali in Task 2:

Terry: The question is if you prepare a complex [she reads a question] .. We can get that out of colour.

Ali: Oh, yeah.

Terry: If it appears green it means, because it's opposite, so green..

[Ali clicked **Cont**; **Click the formula of the compound that absorbed the highest energy light.**]

Terry: .. absorbed the highest energy light [reads the question] .. yeah .. other formula .. Cu(en)_3^{2+} , 'cause you gotta click on formula

Ali: Umm, no, I wasn't clicked on that one

Both: NO!

Terry: Shorter the wavelength, so the higher the energy of course

Ali: Oh yeah, of course it's shorter

Terry: Yeah, shorter wavelengths ... course it's got higher energy

Ali: Of course, the shorter the wavelength, the greatest the ligand field splitting

Terry: It had to be, ..um ... the top one

[They clicked on $\text{Co}(\text{H}_2\text{O})_6^{2+}$]

Ali: No ..

Terry: .. must be the higher light is the greater the field splitting

Ali: higher the energy light

Terry: the greater the ligand field splitting

Ali: Oh, OK

Terry: So was the [thinking]

Ali: was the [thinking]

Terry: so the high energy is the great ligand splitting

Ali: It had the shorter wavelength, so have been high energy and must be the greater ligand field splitting.

Both: OK

In the other example, Paula comments on a conversation with Jim during the Task 3 performance, concluding that there was no benefit in working in pairs:

R: Did you find this conversation with Jim helpful?

Paula: Um, it didn't really make any difference, I mean, I can see how I can get that, ... So, it's got four in total, so it had two in the main valence shell. I think Jim and I were talking about different things at different times.

Some students had a clear preference to work alone so that they could work at their own pace. In one case a mature student expressed discomfort working in the pair because he: "might be a bit slower and it might be confusing having somebody else" (Leo, Task 2).

Among participants there were students who performed the task only individually or only in groups. However, some participants who participated in more than one task worked both individually and in groups. When the responses of those students who participated working both individually and in groups were compared, again the individual preferences were identified. While for example Leo expressed a preference for working individually and did not enjoy working in pairs, Ali and Terry both enjoyed working in pairs.

(c) Computer Familiarity

At the beginning of each interview students were asked about their familiarity with computer use. The collected responses indicated that students ranged from “novices” to “experts” in computer experiences. Although most students had completed a first semester course involving computer use, many would still have benefited from human assistance in helping them identifying software commands/options (Falk & Carlson, 1995). The written instructions were never adequate for students with little computer experience.

For example, Task 4 required the greatest manipulation of files on the computer and a majority of students had difficulty. For example they asked questions such as: “Is this the right place?” “Where are we actually going?” “How do we start it?” “How do we exit this one?” or made the comment “I don’t know what to do.”

(d) Satisfaction

Student satisfaction with the tasks was usually high and the positive attitude of students to CAI instruction delivered to them forms one of the major motivations for continuing the use and development of the chemistry software.

The students taking part in the study had different experiences of using computers, and mixed success with the tasks they attempted, but the majority were overwhelmingly positive about the experience (Table 6.8.) and usually expressed interest in using the software further. Students commented on their experiences as, “was good”, “cool”, “useful”, “helpful”, “I enjoyed that one”, “it’s easier than reading a book”, “I’ll definitely come back and do it again” or similar to that by Dan in Task 4:

I quite like them because they make everything a lot easier .., you don’t have to do lots of writing and sort of stuff, .. and when you are working and fool around to find out what you can do. (Dan)

Students’ comments such as “it is easier than reading a book” or “you don’t have to do lots of writing” are in agreement with findings of the analysis of Fletcher-Flinn and Gravatt (1995). Fletcher-Flinn and Gravatt commented on the advantages of the computers and that “this can probably be attributed to better quality instruction delivered by computers compared with traditional instruction” (p. 230). The authors discussed that “it is likely that the CAI proficiency advantage which has been

consistently reported by reviews in the past is due to more effective instructional material” (p. 230).

However levels of satisfaction did not correlate well with the level of student achievement of intended learning outcomes. For example, when commented on Task 2, Brian explained:

Was easy to understand, easy to go through and explain it well, even though I did a couple of things wrong. (Brian)

It was revealed also that student satisfaction was closely related to the nature of the computer task. The participant responses to the type of software applications are described in the section below.

(ii) Insights into the Software Design that Affected Student Achievement of Intended Learning Outcomes

The observational and interview data also provided valuable insights into the factors relating to software design that affected student achievement of the task objectives. The features of software design for different tasks differed (e.g. running score as a feedback was present only in Task 3); however, omissions and student ability to follow implemented instructions were recorded for all tasks. Table 6.10. shows a summary of student responses on software design.

(a) Feedback

None of the tasks provided feedback that was sufficiently flexible to meet the needs of most of the participants. This was illustrated in Task 3, in which Ali was given two problems requiring an understanding of the influence of lone pairs of electrons on molecular geometry. For the first example she resorted to guessing to get the correct answer to the seesaw geometry for SF₄. She then carefully read the feedback information provided before she went on to the next problem, ClF₃. She determined the number and types of pairs of electrons, but was unable to apply the information she had just been given and again resorted to guessing to complete the exercise.

Table 6.10. Insights into software instructional design and implementation

Insights		Task 1	Task 2	Task 3	Task 4
Software instructional design					
Feedback	useful	5	3	4	-
	moderately useful	4	6	2	-
	not useful	2	1	0	-
	no data	-	1	0	-
- Score	positive effect	-	-	2	-
	neutral effect	-	-	2	-
	negative effect	-	-	2	-
Omissions	serious effect	8	-	-	-
	minor effect	6	10	-	2
	terms	-	-	3	4
	errors -noticed	-	0	0	-
	-not noticed	-	11	2	-
Guessing	used	3	2	2	-
	some	1	4	0	-
	not used	8	4	4	-
	no data	-	1	0	-
Preference	for: computer experiment	3	-	-	3
	real experiment	5	-	-	2
	both	2	-	-	3
	no data	2	-	-	0
Implementing Instructions					
	followed	4	8	4	8
	partially followed	4	2	1	0
	not followed	4	1	1	0

In Task 2, the supplementary tutorial on absorption and colour, students' responses were corrected and then the task moved on to the next topic, leaving the students confused and without information for them to elaborate their conceptions or to deepen their understanding. An interchange between Ali and Terry while doing the task illustrates the confusion:

Ali: What was the colour absorbed by the solution?

Terry: Green.

Ali: Was it green or red?

[They selected (guessed) red.]

Terry: Green...

[Reading the computer response]

No, the purple-coloured $[\text{Cu}(\text{en})_3]^{2+}$ was absorbing green-yellow light.

Ali: Green-yellow.

Terry: We did red because we thought it absorbed opposite on the spectra.

Ali and Terry were tantalisingly close to using the idea correctly but required a little

more information and practice. This tutorial failed to give the students suitable feedback or the necessary background knowledge to enable understanding, but rather just corrected the student's response.

Kevin (Task 2) described:

.. when you got the wrong answer they told you the answer and you had to go back and as they said .. just say carry on and swing back to the question again, .. you should be given out reason why would be the wrong answer, but not actually giving the right answer. So, giving us another chance to guess, give the reason to go back . (Kevin)

The instructional design of the task took little account of the variety of backgrounds of the students and the varied success of students on the tasks bears out the well known Ausubel (1968) comment: "the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly." What is required is a form of adaptive feedback.

Computer Generated Score

Task 3 presented students with a running score of their success. Table 6.10. shows that this form of feedback yielded mixed results, motivating some, but detracting from the performance of others.

For example, Terry, who did not use guessing, was trying very hard to solve the problems in Task 3 (thinking long, looking at the periodic table of elements and seeking a help in the Study Guide). A couple of unsuccessful attempts to solve the problem decreased the running score on the screen. She worried more about the score than the chemistry and the running score disrupted her task performance. Still distressed she asked the researcher:

Does it matter if I come out and it's not right? (Terry)

On the other hand, Paula who was confident with Task 3, explained:

It's nice to have it there [score] you wanna improve it. But I don't know, you do your best anyway, I guess. (Paula)

(b) Navigation

Navigation through the tasks was determined by the linear design of all the software that allowed students only to progress through the task from one proscribed screen to

the next. Some screens had the possibility of going back a page, but not all. If students missed the information, they had to start the task again, and many participants did. For example Jill (Task 1) complained:

I had some problems here and I had pushed the wrong answer, but it didn't say how to go back, what the answer was ..

If you are going well you can keep, you can remember what was going on, on the previous pages, but if you are not, you are losing train of thoughts, you need to go back a page and start again .. (Jill)

(c) *Guessing*

One of the common strategies students used to complete the task when lacking understanding involved guessing. The videotapes of task performance showed that students who were struggling, very quickly decided to guess and were able to avoid confronting some of the task objectives by using guessing. For example Tim, who was familiar with computers, used guessing to a large extent and the help button as a way to overcome problems. His quote from Task 3 was used in describing the use of guessing as a solution for a lack of understanding (see the theme Student achievement of intended learning outcomes described earlier).

Some students admitted how in solving some problems they used guessing:

Cathy: So here [Task 3, Problem 3/10] I was still getting a bit confused.

R: You say you're still getting a bit confused, but in fact there you've got them both right.

Cathy: Probably just guessing.

However, the interviews showed that most students were reluctant to guess and only opted for this strategy when they could not get the information they required from the feedback available (for example Jim when performing Task 3 with Paula or Terry, also performing Task 3).

(d) *Type of Software Application*

As mentioned earlier, the participant satisfaction depended on the type of software applications they used. This indicates how all the contributors in student – task interaction are interwoven. Both the individual characteristics and the software design influenced together student – task interaction and student achievement of the intended learning outcomes.

In Task 4 students were asked their opinions about the animation of the unit cell of NaCl as opposed to the pre-built ball and stick model showing the same unit cell of NaCl:

I like this [pointed at computer screen] 'cause you can see everything what you are doing, it makes it easier to picture it in the head, rather than, sort of, trying to get your hands, sort of trying to mould it there in front of your face while it's all here on the screen. With that [again pointed on the screen] you can tell the sizes and the spaces and this stuff [now pointed at the NaCl unit cell concrete model] you wouldn't be, sort of, able to get a comparative thing. (Dan)

However, the data in Table 6.10. show that in chemistry, the students valued the opportunity to do real as opposed to simulated experiments (Task 1):

I prefer to do it by myself, 'cause I like to have my hands on and play with them, and it's like once I am making a mistake I remember what I should have done in the first place. I don't know what I would remember very much about all these things because it's all written and I'm just stopping to think about that. (Gill)

(e) *Errors, Omissions and Implementation*

All the tasks in the study contained minor errors and/or omissions in software design. These were not always detected by the participants, but often caused disruption to the performance of the task out of proportion to the importance of the error (either consciously or unconsciously).

For example, in Task 3, when solving the shape of a compound, Keith experienced the failure of the program to provide a formula of the compound on each screen page and explained:

I was trying to find the shape, but the formula was not there, .. I mean, if you had the formula up when you're trying to choose the shape then you are, sort of, trying to remember where the lone pairs are and what shape there is in ... (Keith)

To some extent these problems can be overcome by the use of carefully constructed instructions. However, once engaged in any of the tasks that formed the study students usually forgot about the implementing instructions and the value of carefully directed comments was lost. For example in Task 1 (Table 6.10.), the instructions suggested that at least four data points be collected (because of the necessity of distinguishing between a straight line and a curve from the data). However half of the participants missed this instruction and became frustrated with the task.

6.4. DISCUSSION

Research Question 1, namely

How do students interact with different kinds of commercially available software, used in a first-year undergraduate chemistry course?

was further elaborated through a series of questions. Those questions were answered by an evaluation of student achievement of intended learning outcomes and of how different factors affected their achievement. A summary of main insights arising from the study and their relationship to the research questions, stated in section 6.1., is given in Table 6.11.

Table 6.11. The summary of the research questions and main insights given from Study One.

Research Question (given in section 6.1.)	Insights given
1 a) What achievement do students demonstrate of the chemistry learning objectives in the tasks?	More than half the students do not achieve learning outcomes expected by software designers or course coordinator (Table 6.8.).
1 b) How is student performance on software-based task affected by :	
(i) interaction with the software	Influenced by task design, feedback, etc.
(ii) students' prior knowledge	Prior knowledge influences student performance in both cognitive and affective ways $\Rightarrow$ different prior knowledge gaps (other factors: task design, feedback)
(iii) interaction with other students	Important for some (not all) students.
(iv) interaction with the computer hardware	Depends on computer familiarity.
1 c) How do students feel about using computers as a tool to help them learning chemistry?	Positive students' attitudes towards learning with computers.

This study has shown that less than half of the participants were able to achieve the intended learning outcomes in the computer-based tasks being used in the first year chemistry course at Massey University (Table 6.8.). Students seeking a challenge, and those working in groups with a leader who dominated the tasks and requiring a slower presentation, were both frustrated by the tasks.

Student prior knowledge and familiarity with computers are dimensions that the individual student brings along when starting the task, and both influenced student –

task performance (see section Prior knowledge).

The students working in groups differed in communication skills. However, student-student interaction can be stimulated by the appropriate software design.

Student satisfaction is closely related to the task design. It appears that the design of the tasks, which involve a linear presentation of material and non-adaptive feedback, excluded the students with poor prior knowledge, and bored the well prepared, and this was the main factor diminishing the success of student - task interaction.

In addition, a mismatch between the course requirements (e.g. pressure unit in kPa) and the instruction offered in commercial software (pressure measured in Task 1 in mm Hg level) has occurred. Lower (2000, para. 3) argues that “the benefits that well-designed CAI can provide are unlikely to be realised unless it is carefully integrated into the overall course”.

Both themes, *student achievement of intended learning outcomes* and the *factors affected student achievement*, as well as all dimensions of them were described separately. However, they are interwoven and all of them contributed to student – task interaction. Indeed, quite often one student’s quote involves many dimensions and can be used as evidence for multiple aspects of discussions.

In the first aspect addressed here – **Consequences for Software Design**, the two factors that were identified as major influences on student achievement, the prior knowledge that student brings along to the task and the software design, were combined and analysed together.

In the second aspect – **Consequences for Laboratory Design**, the dimensions of software design were analysed through implementation of computer tasks in laboratory classes.

6.4.1. Consequences for Software Design

(i) Linear vs. Branching Design

In all the four cases that were the subject of this study, students were presented with a linear sequence of screens that must be attempted in a tutorial-determined pathway in order to complete the task. A level of prior knowledge is assumed in the task that does not necessarily match the prior knowledge of the students. In each case the tasks were

given to students after the material had been covered in the lecture course. At first, assuming that lectures developed the required understanding, the students would have been expected to have the prior knowledge required to tackle the task. The task is also presented in a fixed number of screens that do not necessarily match the level and order of presentation and/or instruction that would satisfy the student. One mature student, who participated in two tasks, after participating in one task working in pairs, in the next wanted to work at his own pace and spend more time on each screen because he “might be a bit slower”.

The deficiency of the Task 1 design (which was present in all other tasks as well) can be summarised in a description by Jill:

If you are going well you can remember what was going on in the previous pages, but if you are not, you are losing your train of thought. You need to go back and start again ... the program has to be written so if you don't know what it is, you can find the answer somewhere. (Jill)

The analysis resulted in five distinct groups of students who could be identified according to their progress through the task. A summary of these groups is given below:

- Those for whom the task matched their knowledge and required pace of instruction. These students followed the intended learning path as specified by the software designers. Generally these students expressed satisfaction with the task.

For example, Brian (Task 2):

Was easy to understand, easy to go through and explain it well. Even I did a couple of things wrong. (Brian)

- Those with inadequate prior knowledge. These students completed the task by a variety of devices such as guessing but were usually clearly dissatisfied with their performance. For example Gill, an older student who finished high school a long time ago described (Task 1):

I have to go back and sit down and work it out. That was what I found hard because you have to assume that most of the people did Bursary, but for me no .. I didn't know what they were talking about .. (Gill)

- Those for whom the pace of instruction was too fast because too much conceptual information was presented on each screen. This group could not take advantage of the feedback provided to develop understanding and required more detailed feedback and slower paced instruction. For example, Leo (Task 2), a student who described

himself as “ a bit slower”, strongly expressed a preference to perform the task on his own and not in groups because “ it might be confusing having somebody else”. Students such as Casey and Donna (Task 1) who were looking for a more detailed feedback belong to this category as well. The conversation between Casey and Donna in Task 1, as they try to find out “where that seven sixty came from?”, in order to understand the meaning of the pressure of 760 mm Hg (see section 6.3.2. (i) (a) on prior knowledge for a more detailed conversation), shows how the software failed to provide students with the scaffolding they needed.

- Those who were well prepared, and completed the task without serious effort. Often the task took them too slowly through an area of knowledge about which they were already confident. For example Paula (Task 3):

I got a pretty good idea about the shapes of molecules and that sort of stuff from last year, .. I am pretty happy with that sort of stuff. (Paula)

- Those outstanding students who were often dissatisfied because they did not feel challenged by the demands of the task. For example Bill (Task 3):

.. some of the things are very simple .. like what is really obvious, .. some of the things ask the answer like: Is this a straight line? .. It didn't challenge me in any way. I mean, these are all the things we either did in the lectures in chemistry or physics .. it doesn't help me learn if it says what is this/ it's that .. (Bill)

Common design features of all the tasks investigated in this study include: a linear sequence of screens (which had to be attempted in sequence to complete the task), an assumed level of prior knowledge (which did not necessarily match the prior knowledge of the students), and a fixed number of screens (that did not necessarily match the level and order of presentation and/or instruction that would satisfy the student). These features can be matched with the different groups of students identified during the data analysis as is shown in Figure 6.5.

The ubiquitous linear task design is probably a carry over from the traditional chemistry textbook. However the computer is an ideal platform for introducing branched networks into the design of tasks. The need to match the design of instructional software to student needs has been recognised for a long time (Cohen, 1983; Goforth, 1994; Mory, 1994; Whyte et al., 1995). However in a review of educational technology, Kearsley (1998) comments how there has been a sustained attempt to develop more sophisticated

‘intelligent tutoring’ programs, but with a few exceptions this entire line of research has yielded little of practical value. A number of authors assigned nonlinear software design to student-determined learning or a constructivist learning approach (Goforth, 1994; Greening, 1998; Schaefermeyer, 1990). Advocating a constructivist approach to instructional design, Greening (1998) suggests a nonlinear navigation of information should lead to a “democratic” type of learning, rather than a behaviourist approach involving a linear design and “prescriptive” learning.

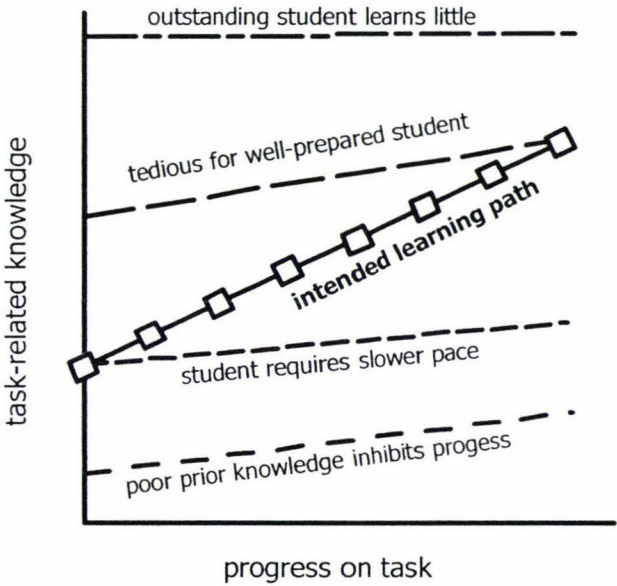


Figure 6.5. Deficiencies of a linear task design.

The need for software to offer students the alternative of both a constructivist and a more prescriptive design is one of the conclusions of a psychology-based instructional software (Windschitl & Andre, 1998). This was one of the factors that play an important role in a design of computer software.

(ii) Feedback

Most of the student-task interaction in Tasks 1, 2 and 3 was designed in a form of asking questions, in which students were led to select one of the options available on the screen or to enter their answer in a form of typing the numerals (digits). Depending on students’ choice or input they were given a feedback that indicated if their selection or input was right or not. The right answers were supported by an appropriate explanation, while in the latter cases students were asked to try again and go back one screen. In the

feedback of all tasks no additional help in which students could find a reason why they might be wrong was provided. Such kind of feedback left for example Casey and Donna in Task 1 struggling to understand the meaning of the pressure of 760 mm Hg throughout the task and completing the task without getting the information needed. Another example is Tim in Task 3 who used guessing as a strategy throughout the task. For example in solving the number of lone pairs in AlCl_3 Tim had three attempts [1, 0.5 and -1 before getting the right answer] and explained:

Tim: Lone pairs, that's what .. I'm thinking five being all together, I just think what actually should have been done here, they are all five, but three are tied up, chlorine took one, sevens .. so it's one mixed up ..

R: When you tried ..

Tim: It's point five .. so it's half [he recalls the episode when he entered 0.5]

R: Ok, I see ..yes, ..

Tim: So, I just thought, once I worked out what the program was, I wanted to see what I could get away with..

I've tried with a negative number, so, there could be only a bigger one after..

When interacting with CAI students should be provided with adaptive feedback. Adaptive feedback is a feedback that directs students to different destinations depending on their answers and provides the students with the information they need. Adaptive feedback is a topic of active investigation and development (Goforth, 1994; Mory, 1994; Whyte et al., 1995), but was not found in any of the software investigated.

Evaluating the effects that influence student learning, Hattie (1999) described feedback as "the most powerful single moderator that enhances achievement" (Television, para. 6). This study showed that the quality of feedback, and the way in which it moulds the task to fit the individual, had a major influence on the utility of the task and should be one of the major factors considered when choosing software. The temptation when selecting software is to focus on the content and its presentation, rather than the way in which the software will be experienced by the student. Hoffman and Lyons (1997) recommend the evaluation of software using an evaluation instrument in which feedback is placed last in the series of factors involving the instructional design. However the level of feedback is an area of development identified in the computer education literature (Mory, 1994), and has to be considered in the development of chemistry-based applications.

One of the possibilities is that CAI tasks will allow the integration of students' alternative conceptions into the learning experience in courses to a much greater extent

than has been possible hitherto. Studies such as the one described here can be used to target the identification of alternative conceptions, and CAI tasks could be adapted to allow the student to explore these conceptions and compare them with scientifically accepted versions.

6.4.2. Consequences for Laboratory Design

The question of the role of computer in aiding learning in the laboratory and in the case of simulated experiments in replacing laboratory work is an important one. The descriptions of the role of software in regular laboratory classes given by students provided important insights into the selection of and implementation of commercially available software in regular laboratory classes.

It has been indicated that Tasks 1, 2 and 4 were part of regular laboratory classes. Task 1 and Task 2 are very similar in design, each using a linear sequence of screens in which students perform the experiment, observe what happens and interactively record the observed results (measurements). Both tasks are written by the same authors and were distributed to the market in the same year (Smith, Jones & Gammon, 1992). However, Task 1 (a simulated Boyle's Law experiment) was implemented in the laboratory class as a separate experiment and was not directly linked to the other experiments being carried out during the laboratory session. Task 2 (a tutorial on colours and absorption spectra) was used as a supplementary tutorial and directly linked to the laboratory experiments being carried in a laboratory session.

Out of data analysed, two insights were extracted -

- a) the role of software in simulation i.e. replacing an experiment.
- b) the role of software in complementing an experiment.

(i) Simulations

Draper (1998) pointed out that it is frequently claimed that simulations are leading examples of how the use of computers can benefit education in the sense that they can allow students to explore situations that are dangerous, too expensive, or ethically unacceptable to explore in a lab.

Task 1, a simulation of Boyle's Law in which students explored the pressure - volume relationship of gases, was implemented in the laboratory class and was not connected to

any of the other experiments being carried out during the laboratory session. Students were introduced to the concepts at the lecture. However, although the laboratory session addressed the properties of gases, no related practical experiment exploring the same law, as given by the computer simulation, had taken place. It is possible that a real, practical demonstration of how a manometer works would provide concrete examples (supported with an implementing instruction sheet or an appropriate outline in the laboratory manual) and would have, for example, helped students to understand better the meaning of the atmospheric pressure of 760 mm Hg, and to overcome other difficulties such as those described by Donna and Casey earlier (see section addressing *Prior knowledge*).

Most of the students participating in this task failed to understand how the equipment worked (Table 6.8.). For example, Terry described her confusion:

.. should the piston be clamped? .. Um, .. I think, I was thinking about it, when I was getting confused, I was thinking about,.. they actually were clamped on the outside of the, hold on, and when I say should the piston be clamped, I mean, I know that the piston is moving up and down [uses her hands to demonstrate it] but I was trying to visualise how could you clamp it, do you see what I mean, I was thinking of how could you actually clamp it ... I think I was more thinking about the clamp on the outside for some reason .. yeah (Terry)

Another student described the inability of the software to provide a real, three-dimensional representation of the apparatus:

When the apparatus was set up, I was not able to understand whether it was present in front or back of the manometer. I was not able to get a 3D picture, So, in that way I was a bit confused ... but, if I've seen that in the lab, then I would know, um, I would have done the connection, I would know where is what. I haven't done this experiment before. So, after I've seen this set up I just realised that I didn't know where they are actually connected. So, I just got confused with this .. doing it at computer is just blank .. (Dave)

The other important dimension that emerged is the completion of the assigned task without understanding. This was more evident towards the end of the task in which students were asked to graph collected data, to discuss them and to answer the questions in their laboratory reports. For example, deriving the two straight lines, one for the pressure - volume relationship (due to just two data points collected) and the other for pressure - inverse volume relationship, Tim talked about his way of graphing and interpreting data:

.. from what we were told, pressure on the y axis, we have to put it all the time, so measure anything else that is against pressure along x axis ..
So, initially I tried the straight way, so when I ended this way, what I found was the line going in a negative instead of a positive way, .. that way I found it didn't look right. They have to be in a linear fashion positively and I came back and thought why, so I thought aha, try around and try other combinations to them, so I tried yeah, that was first, also I didn't have enough points. Also I found the line is going down, in the wrong way once I completed those two graphs I didn't have enough data to get the last section .. (Tim)

Draper (1998) discusses how completing a computer-based assigned task involving simulation without understanding could be due to the same reasons as completing any other laboratory task without understanding. The crucial pedagogical weakness of many labs is the failure of students to be intellectually engaged with the conceptual issues, because they are wholly occupied by the mechanical procedure, by following a fixed set of steps, and getting the official 'result'.

Student specific factors, such as a lack of prior knowledge about a concept, which affected their performance on task, cannot be changed easily. The software design allowed students to complete the task without checking that they achieved the intended learning outcomes. For instance, Tim used guessing as a strategy to match the picture in his mind (the direction of straight line regardless of what relationship it represents). It also emerged that students missed or failed to follow the supplementary instructions. Students were given supplementary instructions in their laboratory manual book about how to manipulate the program. This is an insert from the instructions (23.102 Chemistry I (b), Laboratory Manual, 1997, Department of Chemistry, Massey University):

Select 3. *Volume - Pressure* and *Run the experiment* in which pressure and volume are varied at constant temperature. Click *Push* and *Pull* to establish the maximum and minimum pressures allowed by the apparatus design. Use *Record data* at the highest and the lowest possible pressure, and any two other pressures then *Go On*.

The students were asked to explore the graphical relationship of both pressure-volume relationship and pressure-inverse volume relationship. Although it is suggested that at least four data should be collected, half of the participants missed this instruction and collected only two data points, resulting in a straight line instead of a curved pressure-volume relationship.

Finally, the majority of students expressed preference for a real experiment instead of simulation on the computer:

I prefer to do it by myself, 'cause I like to have my hands on, and play with them, .. and it's once making a mistake I remember what I should have done in the first place. I don't know what I would remember very much about all those things, because it's written, because I'm just stopping to think about that. ... but, if you weren't here I couldn't go any further, ..., so yes for doing an experiment is quite good if I have a very good idea what is supposed to be done and I can scratch through and figure it out, ... but, doing the scratching of what you have never done before, **not**, it wouldn't do for me. (Jill)

This comment highlighted the importance of concrete personal experiences. Laurillard's model (as cited in Draper, 1998) assumes that in all subjects there are two levels whose relationship is often neglected in teaching, the formal conceptual level and the level of practical action and personal experience. However, in chemistry, according to Johnstone (1991), not two but three domains must be related, the macroscopic domain of bulk properties (including what chemicals look like in the lab), the formal domain expressed in equations that typically express attributes of a single molecule and a third domain of the spatial and temporal (dynamic) properties of molecules and how they fit together.

Draper (1998) argued against the use of simulations to replace the laboratory experience in a way that allowed students to follow a set of steps without being engaged with the conceptual issues. However, the author indicated that simulation and animations "may sometimes be just what is needed" and could provide a deep pedagogical motivation if used to address the conceptual gaps (for example simulating the unseeable domain).

The comments such as the one by Terry ".. can't be clear because we certainly didn't do it.", suggest that the simulation failed to replace the clarity that could be achieved by doing the real experiment.

In conclusion, from the students' comments about Task1, derived from this study, when performing the simulated experiment, many students:

- failed to develop understanding of details of the equipment (e.g. how syringe and U tube are connected);
- completed the assigned task without understanding;
- wanted "hands on" experience.

(ii) Software in Assisting Learning

Task 2, a complementary tutorial on colours and absorption spectra, was well received by students. Table 6.9. indicates that most of the participants expressed satisfaction in performing Task 2, compared to the number of students being satisfied with simulated Boyle's Law experiment (Task 1). For example, a student who participated in a couple of tasks including Task 1 and Task 2 explained:

Ali: I didn't enjoy this one (Task 1). I don't know the answers, you know like Um, it was not as enjoyable a subject I found it boring as well. I think we made We got everything wrong, didn't we?... I quite enjoyed the first two [Task 2 and Task 3], definitively, I enjoyed them ... I quite enjoyed the transition metal complexes and colours ... (Task 2)

Some of the participants indicated that having a computer part as a supplement to a real experiment would work the best for developing conceptual understanding:

I think you learn more with the computer because like if you just run the practical part you don't have to think about it, you just do it ... coming to the computer part should help restructure what you've just done and it's good because it shows in a basic form .. I think the computer program is very important 'cause it helps you to reinforce ideas you should be thinking about doing the experiment. .. Otherwise you do the experiment and keep on thinking.. oh, let's get as fast as you can, and don't think about it as when you come here, you have to sit down and think about it, which is good. (Terry)

According to students' description, a lot of learning takes place by practically doing the experiment. Laboratory session was the context for three tasks in the study and the participants discussed the type of computer-supported applications in the context of laboratory classes. Task 1, computer simulation, replaced the hands-on experiment and the students compared the learning by this simulation with hands-on kinds of learning. The results of this study suggest that, to some students, a computer simulation failed to provide the experiences that would enable them to develop understanding and achievement of intended learning outcomes; in desperation they talked about how they would learn more by performing real, concrete hands-on experiments in the laboratory. Hands-on learning was not analysed in this study, so it was hard to discuss the differences between the two; instead the comments of what the students have said and the comments found in the literature are given. On the other hand, the students appreciated the computer-based tutorial as a supplement to an existing "on hand" experiment (Task 2), because it helped them grasp the conceptual demands of the laboratory session.

6.4.3. Other Insights

(i) Group Work

The use of computers by pairs of students provides students with an excellent chance to practice verbalizing their ideas about chemical concepts. Examples of good cooperation between the students working in groups, in which the students verbalised chemical concepts, were found in this study (e.g. Donna and Casey in Task 1) This is in agreement with Ruberg et al. (1996) who found that on-line interaction stimulated students (19-20 years of age, all biology majors), constructing meaning by taking time to put their newly learned concepts into their own words, even those who never spoke in face-to-face settings. This is also in accordance with Vygotsky's sociocultural perspective of constructivism, but this perspective has not been the main aim of the study and was not explored in detail.

In some ways the computer is a more suitable vehicle for encouraging this type of interaction than the traditional chemical laboratory where problems involving the practical techniques and equipment often dominate the conversation. Ruberg et al. (1996) also point out that the success of computer-mediated tasks depends on the selection and structure of the task and the teacher's role in providing links to other pre-existing and upcoming learning activities, but according to the findings of this study that has not occurred. Appropriate questions in the implementation of software can be used to enhance the conversations and in the future such strategies may be programmed into CAI tasks. To the researcher's knowledge, at the time this study started, apart from the information of the use of computer-based applications in chemistry in general and the survey collected from the students about their opinions of different teaching strategies used in the course, no educational research has been employed in terms of adjusting the computer-supported applications for effective cooperative learning. Students were advised to work in groups because of the number of computers available compared to the number of students attending laboratory class.

(ii) Evaluation of CAI

When the students' opinions about the Chemistry 23.102 course were surveyed back in 1996, the students' responses about the use of computers in the course were compared to those obtained for other components of the course (lectures or laboratory classes, for

instance). The positive student attitude towards computers, as well as all other results reported in this study, were collected from a small sample size and were not compared to any results obtained from other components of the course. First, the effect of the components, other than the use of computers in Chemistry 23.102 has not been investigated for the same course. Second, in the computer environment 'new kinds of learning' take place (Marton, 1999) and it is hard to compare one 'new' kind of learning to another 'traditional' kind of learning. This is in accordance with the Hattie (1999) statement in which the author suggested not to compare having computers with not having computers. Therefore, there is no need to compare the results obtained for the use of these particular pieces of CAI in this course to the literature results on the effectiveness of laboratory classes or lectures, for instance.

However, the computer use cannot be evaluated by itself alone as it is mostly used as a supplementary tool to other components of the course (lectures, lab classes etc.). For that reason the aspect of the computer effectiveness when implemented in laboratory classes uncovered insights that can be very useful, not only for teachers, but also for software developers.

The results obtained in this study generally agree with those obtained from the research on computer use in other science disciplines (physics for instance, Roth, 1995; Roth et al., 1996) and with the general trend of the effectiveness of CAI reported by Fletcher-Flinn and Gravatt (1995). This qualitative study disclosed many advantages interwoven with some disadvantages of computer use in chemistry (Roth et al., 1996, named them affordances and constraints).

Although the type of research was not the same, or the level of chemistry of the participants was not the same, the general comparison of the main findings of this study with the results of other studies of CAI use in chemistry (Eggert et al., 1992; Williamson & Abraham, 1995; Yalcinalp et al, 1995) brought about the conclusion of a commonly experienced mismatch between the promises the CAI should offer (to provide constructivist-based student-centred learning, to provide instruction that enables a learner to compare their conceptions with those accepted by the scientific community, to provide instruction of chemistry concepts in a way not achievable using other teaching strategies and tools etc.) and the outcomes as experienced by students.

(a) Stimulated Recall Interviewing

The stimulated recall interviewing provides a very powerful tool for analysing the use of CAI tasks by students. Data can be obtained during both the execution of the task and from the subsequent interview. Further, with practice, the interview can be used to tease out levels of understanding to provide a clear focus on student conceptions. The method, as used in this study, represents an advance on the use of the think-aloud protocol that was advocated nearly ten years ago (Nakhleh & Krajcik, 1993; Simmons & Kinnear, 1990; Krajcik, Simmons & Lunetta, 1988). The key advantages of the stimulated recall interview are:

- the participant completes the task without interruption from the investigator.
- the subsequent interview provides an opportunity to probe the points in the task at which critical information is missing from the task record, as well as points requiring elaboration while simultaneously reviewing the execution of the task as recorded on the videotape.

6.5. CONCLUSIONS

This study has shown that the computer-based tasks being used in the first year chemistry course at Massey University promoted achievement of intended learning outcomes of less than half of the students who participated in this study. This can be attributed to the design of the tasks, which involve a linear presentation of material and a lack of appropriate scaffolding excluding the students with poor prior knowledge, and boring the well prepared. Students seeking a challenge and those working in pairs and requiring a slower paced instruction and/or different presentation were both frustrated by the tasks. The linear design failed to provide student centred (determined) learning as advocated by the constructivist learning approach.

The quality of feedback has a significant influence on the usefulness of the task and should be one of the major factors considered when choosing or developing software.

Computer-based tasks with the 'expert' designed information and appropriate scaffolding can assist students to construct knowledge for themselves (Vygotsky's social constructivist point of view). Computer-based tasks offer students an opportunity to negotiate their conceptions with those accepted by the scientific community. This

particularly can be successfully achieved in cooperative groups. The study revealed the power of computer-based tasks to facilitate student discussion of chemical ideas when students work cooperatively.

A message for educators choosing or implementing current software is that the types of task studied here are very useful for only certain groups of students (they excluded students with poor prior knowledge but also did not challenge outstanding students). The matching of the type of task to a variety of individual student's needs would increase student satisfaction and acceptance of CAI.

The next message for teachers, educators and administrators (interested in saving money by replacing laboratory work with computers) who would like to use current software to replace practical laboratory classes (whether using computer simulations of the experiments or computers to assist learning), derived from this study, is that a lot of learning takes place by practically doing the experiment and that the students appreciated the computer-based tutorial as a supplement to an existing "on hand" experiment but not as a replacement for real experiments.

The discussion that addressed the factors that might cause the mismatch of CAI promises and the outcomes observed, ended up with suggestions that were taken into account in the later studies of the thesis.

Finally, learning with computers provides different kinds of learning and should not be evaluated by comparing with learning using other educational tools. Qualitative methods such as those used in this study can play an important role in evaluating computer-based learning tasks. The stimulated recall interview provided a very powerful technique for analysing the use of computer-based tasks by students.

The insights of this study (student satisfaction with the type of software application and the concept addressed, inadequate software design with linear sequence of screens and with no adaptive feedback) are considered in the next step of the project - Study Two, which is described in the next chapter.

7. STUDENT USE OF THE IN-HOUSE DEVELOPED STEREOCHEMISTRY TUTORIAL - STUDY TWO

The findings from Study One indicate that student achievement of intended learning objectives was influenced by two factors – those related to student characteristics, and those related to software design.

The student's characteristics are those that the student brings to the task. These personal characteristics, which are the product of social, cultural, economical and former educational interactions cannot be easily changed (Entwistle, 1992). What can be changed is the carefully designed instruction given by the software that might assist the student in making decisions, influencing his/her attitude and therefore the student learning.

In this, Study Two, that was done in 1998, an attempt was made to improve student learning of stereochemistry by a group effort of developing a computer-based tutorial (development phase of the study) and examining the learning by students when using the tutorial. The own-authored software development followed Lower's (2000, para. 3) argument, stated in the discussion of results obtained in Study One, which pointed out that the benefit of CAI can be realised only if it is carefully integrated into the overall course.

7.1. DEVELOPMENT OF IN-HOUSE AUTHORED STEREOCHEMISTRY TUTORIAL

Development of the in-house authored tutorial was based on the research done in Study One and the research in the literature, which described the use of software in teaching chemistry.

The results of Study One, which explored student-computer interactions with commercial software in the first year chemistry course, were used to drive the development of the in-house tutorial. These findings informed about:

- the selection of topics for computer-based tutorials,

- the design of computer-based tutorials,

and suggested that the chemistry topic, addressed by a CAI task should be carefully chosen to take advantage of the special features of both the chemistry concept being addressed and of the computer software over the traditional teaching tools rather than, for instance, replacing a real experiment or a treatment of some topic in the same way as in a textbook.

7.1.1. Selection of the Topic for the Tutorial

Stereochemistry, which concerns the nature of molecular shape and its significance for physical and chemical properties, has been identified as difficult to understand (Barta & Stille, 1994; Black, 1990). There are reports in the literature of attempts to revise the existing models and to develop new models for the teaching of stereochemistry. Therefore, stereochemistry provides an appropriate challenge for new teaching aids, such as computer-based learning.

It has been suggested that the difficulty in understanding stereochemistry arises because understanding stereochemistry requires the use of specific stereochemical terms as well as the need to switch between the microscopic, symbolic and macroscopic aspects of chemistry (Gabel, 1999; Johnstone, 1991) but also 3D visualisation skills (Tuckey et al. 1991; Tuckey & Selvaratnam, 1993). All these aspects were described in Chapter 3.

Computers offer the possibility of designing the instruction in symbolic, microscopic and macroscopic representations of stereochemistry and therefore give students the opportunity to explore and practise the use of different representations, to switch between them and to integrate all of them and build a more developed understanding of the phenomena, similar to that of the professional chemist. Bowen (1998) argues that the computers can be used not only to deliver instruction but also to test or measure student understanding across different ways of thinking (symbolic, microscopic, macroscopic).

In order to help students to overcome difficulties when learning stereochemistry, new methods of teaching are desirable. There is evidence in the literature of continuous attempts to develop new methods for teaching stereochemistry. According to the Hawthorne effect, well known in psychology, the act of implementing new methods that students are not familiar with, can of itself have positive learning outcomes (Pankuch,

1998). The students feel that something special is being done for them and they perceive the problem differently if the lecturer is giving them attention that seems special. CAI is still a relatively new strategy in teaching and should give positive gains if it is used appropriately.

Draper (1998) concluded that no generalisations can be made about what feature of technology or software type makes a piece of CAL successful, except that the most definite successes seem to come from a close fit between a piece of courseware and its situation of use that is specific to that niche (i.e. designed to assist students meet intended learning outcomes). In this study the team members analysed what was particularly weak in an existing situation and thought of how technology could be used to address the bottleneck.

Many chemistry educators and teachers recognised that learning stereochemistry is a very demanding conceptual task and have seen computers as a potential help in teaching these complex concepts (Parrill & Gervay, 1996). The advantage of computers over the traditional educational tools (e.g. textbooks, blackboard) is in giving the students the opportunity of interactivity with on-screen molecules, in which the rotation and observing molecules from different points of view are possible. Such mental operations are identified as necessary skills required for dealing with many stereochemistry concepts. Although students had practised the use of concrete models previously, this new kind of interactivity provides the learner with the opportunities to practise and develop visualisation skills in a different way. Marton (1999) described how “the advancements in applied electronics and information technology in particular open up possibilities to bring about variation in the learning environment in respects that have been unimaginable previously” (p.15).

The outcomes of this study could have implications for the development of other chemistry teaching software. The results of the study also could contribute to the teaching of stereochemistry in general, beyond the computer-based teaching.

7.1.2. Designing of the Computer-Based Stereochemistry Tutorial

The computer-based tutorial was aimed at developing and refining students' concepts of stereochemistry following their instruction on this topic in the lecture course, therefore,

to be used as concept reinforcement rather than introductory. The tutorial aimed to help students achieve the intended learning outcomes of the course they were completing. For that reason, the learning objectives in this research were related to those listed in the study guide. From the teaching perspective, the use of software is seen as a contribution to main teaching strategies in the course, namely lectures, tutorials and laboratory classes. From the learning perspective, the use of software is seen as helpful in providing the students with an alternative. The tutorial was not a compulsory part of the course, but optional (for those who prefer to use computers rather than reading a textbook, for those who need additional challenges and problems to solve, for those who need additional perspectives of the concepts, etc.).

As found in Study One, the commercial software, introduced to first year students in 1998 at Massey University, enabled achievement of intended learning outcomes in only limited numbers of students. Analysing the possible factors that influenced student - software interaction, apart from student prior knowledge, one of the major factors was attributed to the linear student progress and the lack of free navigation (Pavlinic, Wright and Buckley, 2000).

These and other findings from Study One (that arose in response to Research Question 1, given in Chapter 4) were considered by three-team members when designing the computer-based stereochemistry tutorial. The three-team members, involved in designing of the tutorial, were the chemistry lecturer and also supervisor, the chemistry computer technician with prior experience in software design and the researcher. In the design of the tutorial apart from the selection of the topic to be addressed (stereochemistry) and the structure employed to address the topic, particular attention was given to software design.

All team members were involved in teaching chemistry at university level for a number of years (two team members have high school chemistry teaching experience as well) and their PCK influenced the design of the tutorial. They were aware of the features that make stereochemistry difficult to learn (those were listed in section 3.1.4.).

In teaching of stereochemistry at the lectures, the lecturer used a number of teaching strategies/tools including demonstrations, the use of physical or concrete ball and stick models, analogies, telling stories with a support of computer-based applications. The positive students' responses to these teaching strategies were found year after year in students' evaluation forms (given to the students to complete at the end of the course).

From the experience of team members and in agreement with the literature (Gabel & Sherwood, 1980; Ingham & Gilbert, 1991; Staver & Halsted, 1985), the use of concrete ball and stick models was found useful in teaching stereochemistry. Apart from their use in lectures, the positive students' responses in using concrete models were observed during the laboratory classes in which the students had an opportunity to handle the models on their own. The team members agreed that a computer supported application with 3D on-screen models and a possibility to rotate them, in addition to 2D symbolic structures, may be used as an additional strategy to reinforce the student learning of stereochemistry.

The computer-based stereochemistry tutorial was composed using **H**yper **T**ext **M**arkup **L**anguage (HTML) and Java Script and various **M**ultipurpose **I**nternet **M**ail **E**xtension (MIME) types such as image/gif, chemical/x-pdb and video/quicktime files. This way of designing was chosen because:

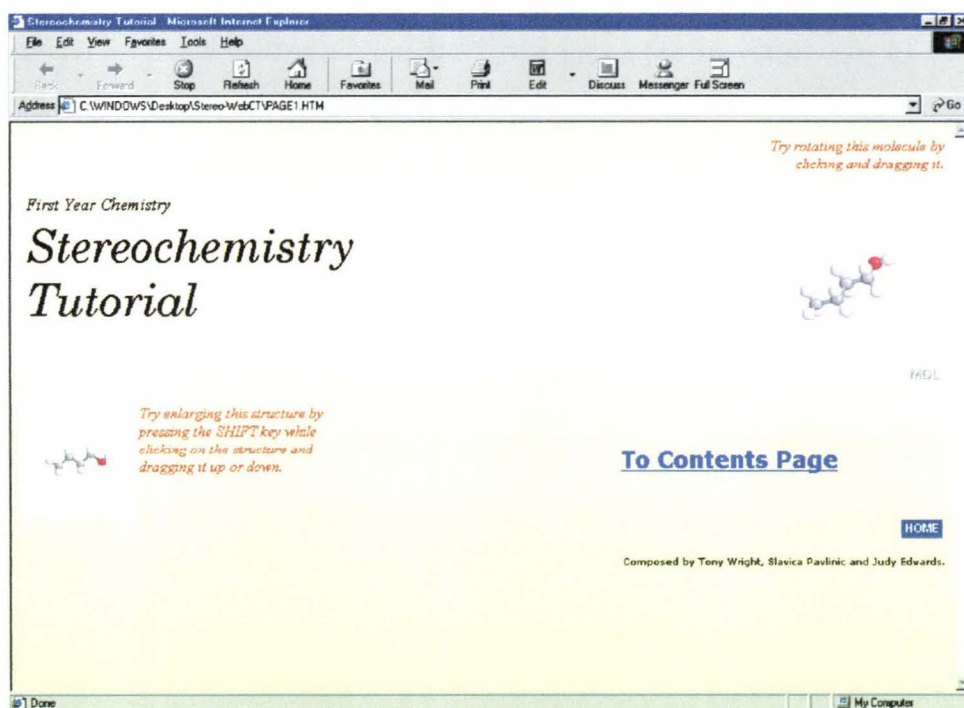
- the tutorial was designed for the Internet use with an opportunity to be integrated into the local WebCT, enabling access by all students enrolled in the course (from inside the campus, but also from home);
- it provided an easy back and forward navigation;
- the designing of the tutorial was straight forward, even for the researcher who was a novice in that field (no computing science background was required).

The two-dimensional representations (2-D structures) were made using Chem-Draw drawings for chemical formulae and inserted as image/gif files while the three-dimensional representations (on-screen 3-D interactive models) were made using Chem3-D molecular modelling program and inserted as chemical/x-pdb (Brookhaven Protein Data Bank atomic coordinate entry - PDB) files. Chem-Draw and Chem3-D molecular modelling programs were already in use (also by the first year undergraduates) in the Chemistry Department at Massey University. The pdb files can be viewed with a helper application (RasMol) or plug-in (Chime), both available to be downloaded free from the Internet.

The use of the tutorial aimed to make an additional help in student learning of stereochemistry. The tutorial with different, textual and pictorial, static and dynamic representations aimed to address a range of learning needs and approaches. The interactivity provided by the tutorial aimed to enable learners to control the pace of their

learning, and to gain further representations where they have difficulty matching their conceptions with those presented in the course material. This is in agreement with Beetham (2000) who described the use of computers as a mediator for discussion, negotiation and tutor support in scaffolding the learner's interaction with the resources and activities provided as a main contribution by the use of multimedia learning. This view can be supported by practical implications of Laurillard's social constructivist and conversational theory (Laurillard, 1994).

A feature of the tutorial is that it offers the student the opportunity to interactively manipulate the on-screen 3-D models, and this was introduced immediately at the front page of the tutorial as shown in Figure 7. 1.



Stereochemistry tutorial. 1998

Figure 7.1. The front page of the Stereochemistry tutorial.

(i) Multiple Representations

Bruner (as cited in Doll, 1993) explained his belief in the way multiple representations of the world influence intellectual growth:

I am convinced that we shall do better to conceive of growth as an empowering of the individual by multiple means for representing his world, multiple means that often conflict and create dilemmas that stimulate growth.

As the chemistry world is built up of abstract concepts that can be represented in many different ways, getting practice in becoming familiar with the diverse ways the chemistry is represented can stimulate students in the understanding of the world of chemistry (Pankuch, 1998; Parrill & Gervay, 1996).

The use of multiple representations (2-D and 3-D) for representing chemical (and stereochemical) compounds is known and present in chemical practice. Two such representations, 2D skeletal formulae (also called line structures or line diagrams) and on-screen interactive 3D ball and stick models were used in the tutorial. Although these representations were used in the chemistry course (i.e. lectures), in a regular classroom, students had never given enough time to practise their use, and make connections between these two different representations. Because the two ways of representing molecules in the tutorial had not been extensively used earlier, these representations appeared to the students as two 'new ways' of representing molecules.

The approach undertaken in the tutorial is an attempt to encourage students to make connections between the 2D skeletal structures and the 3D on-screen interactive ball and stick models, used for representing stereochemistry concepts.

(ii) Content Structure

The computer-based stereochemistry tutorial consisted of three problem-solving exercises (Exercise One – Exercise Three) and a glossary. Approximately half an hour was estimated as the time required for completion of the exercise part. The glossary includes a description of all stereochemical concepts and terms, the concepts underlying the understanding of stereochemistry, and all of them are supported by examples and simple problem exercises. The aim of the glossary was to enable a student to check the meanings of different stereochemical concepts while progressing from Exercise One to Exercise Three.

The tutorial set up of exercises and the glossary followed the objectives that were clearly stated in Part 6 of the study guide (Table 7.1.). Different teaching methods, lectures, tutorials, laboratories including different strategies/tools for conceptual development (e.g. use of physical models) combined with the support of this tutorial during the course all aimed in helping the students to develop understanding and

achievement of the listed objectives. This study investigated the contribution of the tutorial in achieving these intended learning objectives, in particular the contribution of the problem solving exercises in achieving the learning objectives that were selected from the list.

Table 7. 1. A list of the objectives stated in Part 6 of the study guide Chemistry I (a).

Objectives - Part 6 of the study guide Chemistry I (a)
• Draw pictures of molecules containing tetrahedral, trigonal planar, and trigonal pyramidal atoms, indicating bond angles and relative bond lengths. • Draw 3D formulae, sawhorse formulae and Newman projections. • Describe the difference between stereoisomers and structural isomers. • Describe the difference between conformational and configurational isomers. • Define chirality and recognise the presence of stereocentres in molecules. • Define enantiomers and diastereomers and explain the difference between the two pairs of isomers. • Recognise the conformational isomers possible in molecules and distinguish between staggered and eclipsed conformations of molecules. • Draw and predict the relative energies of gauche and anti conformers. • Distinguish between torsional, steric and angle strain in molecules. • Analyse the contribution to strain in chair and boat forms of cyclohexanes and predict relative energies. • Describe the process of ring flipping in cyclohexanes.

Revised: 1998

All of the listed objectives were addressed in the glossary part. The exercise part was focussed on getting students to practise the application of the stereochemical concepts using molecules that can be found in real life. The exercises included identification of and distinguishing:

- different types of isomerism (e.g. structural isomers and stereoisomers),
- different groups of stereoisomers
 - conformational and configurational,
 - enantiomers and diastereomers,
- the concepts related to isomerism (e.g. stereocentre; bonds that could rotate).

Passing through the tutorial from Exercise One to Exercise Three, stereochemical concepts were tested over and over again with increasingly complex organic molecules. This is in agreement with a model progression, described by De Jong and Van Joolingen (1998), in which the regulative learning processes can be facilitated by a

progression in which the model increases in complexity. A model progression with different orders or degrees of elaboration was described as a successful strategy in enlarging a student's intuitive knowledge (De Jong & Van Joolingen, 1998). Parrill and Gervay (1996) also described how their Stereochem Game tutorial employed twenty questions that gradually increased in difficulty through the use of more complex examples.

To match the course requirements and to get students practising with the problems driven by assessment, the examples in the tutorial were selected by the course coordinator. In Exercise One the stereochemical concepts were explored using C4 Alcohols. The aim of the exercise was to test the student's ability to distinguish isomers using the examples of molecules students should be familiar with from high school (NZQA, 2002; Barns-Graham, 1998). Then the same stereochemical concepts were tested using the more complex examples of terpenes (Exercise Two) and finally using the even more complex prostaglandin molecule (Exercise Three).

Exercise One (C4-Alcohols) tasks are designed using either 3D on-screen interactive ball and stick or 2D skeletal structures for representing organic compounds. To make sure students understood the representations, they were given the stereochemical problems using one representation at a time. The tasks in Exercise Two (Terpenes) are designed starting from the use of both kinds of representations, leaving the students to choose the representation they preferred in investigating stereochemical problems. In this exercise the aim was to give students practice in exploring multiple representations and switching between them. As a student progressed through this exercise the way of representing molecules gradually moved towards the use of skeletal structures only. Finally in Exercise Three, the prostaglandin molecule was presented in a skeletal form only, as the symbolic way of representations is mostly employed for complex molecules. Although the link to the glossary was always available, in Exercise Three, additional hints were also available to help students to analyse the complex prostaglandin molecule. For example, when looking for the number of stereocentres in the molecule, by clicking on each carbon atom a student was given a hint informing him/her of the meaning of the term stereocentre.

(iii) Branched Design Involving Adaptive Feedback

In designing this tutorial the group members were led by the main insights provided by

Study One and the computer-based task was designed in a branched fashion. This design enabled students to take their own pathway through the task. More capable students were able to move through quickly to check that they had mastered the concepts while others were able to construct knowledge as they needed it. Such a design would take better advantage of the potential of the computer to provide individualized instruction.

A nonlinear, branched design (advantages of such design were described in Chapter 4, section 4.1.2.) enabled free or student-determined navigation through the tutorial. Adaptive feedback and the links to the glossary were available from each exercise.

The glossary itself provided a list of stereochemical terms and a tree-diagram which showed the relationship between different types of isomerism. Each term or the type of isomerism was hyperlinked to a brief description with an example. Additionally, each description was supported by adequate practice examples. The design employed enabled the students to browse and compare terms, as well as to easily return back to the exercise.

The summary of the tutorial design, including the examples that illustrate the model progression from simple to complex molecules, the multiple representations, and the navigation links available in the stereochemistry tutorial, is given in Table 7.2.

Three exercises can be viewed on the CD ROM Stereochemistry Tutorial. This is a version of the tutorial, amended in Study Four, with slightly amended feedback and having swapped questions a) and b) in Exercise Two. However the structure of the tutorial and the problems for the first three exercises were kept the same.

Table 7.2. The summary of the features employed in designing of the stereochemistry tutorial.

Design features	Example
non-linear; easy navigation; adaptive feedback	<pre> graph TD CP[Contents Page] --> SG[Stereochemistry Glossary] CP --> E[Exercise] CP --> PR[Problems Review] SG --> PC[Problems/Concept] E --> F[Feedback] PR --> F PC --> F F --> IS[Interpret the Structure] IS --> P[Problems] P --> F </pre>
2D and 3D representations	Exercise One
model of increasing complexity	Exercise Two

Pavlinic, 1998

7.2. INVESTIGATION OF STUDENT USE OF THE TUTORIAL

In this research phase of the study, the use of the tutorial was tested on participants.

7.2.1. Research Questions for Study Two

The main Research Question 2:

How do students interact with an in-house authored computer-based tutorial of chemical concept – centred design?

given in Chapter 4, section 4.4., is addressed in this Study Two. This main Research Question was further refined into a series of questions, formulated to provide the focus for this study:

2 a) How do students experience stereochemistry concepts integrated with the specific features of software design?

- (i) adaptive feedback
- (ii) navigation options
- (iii) use of colours
- (iv) interactivity

2 b) What achievement of intended learning outcomes of stereochemistry do students demonstrate, immediately after the tutorial use?

2 c) How is student-tutorial performance affected by:

- (i) the use of different, 2D and 3D representations
- (ii) the navigation options to glossary, the adaptive feedback and the availability of hints
- (iii) the increase of complex molecules and the representation used?

2 d) How do students feel about the tutorial?

7.3. SETTING OF THE STUDY

7.3.1. Students and Sampling

To probe student interaction with the in-house authored stereochemistry tutorial, in 1998, at the end of their regular chemistry lecture class, students were orally asked to participate in the study. Additionally, a sheet calling for volunteers was given to the students and eleven volunteers replied, eight females and three males. Although four of them worked in pairs, the interviews were conducted individually. In this study, no criterion of equal gender profile of volunteer selection was employed. Table 7.3. shows the profile of the participants in Study Two.

Table 7.3. Participants volunteered in a study exploring students' use of computer-based stereochemistry tutorial (Study Two in 1998).

Criteria/variables		Student proportion	
		Number	%
Gender	Females (F)	8	73
	Males (M)	3	27

Posthinc, 1998

7.3.2. Techniques in Data Collection and Data Administration

Data were collected using the stimulated recall interviewing, a technique described in Chapter 5, and also used in Study One. In order to minimise the influence of the presence of the camera on students' performance as much as possible, the computer and all other devices were placed in the practical laboratory. In addition, as the task performance took place, the researcher made field notes on the observational sheets that were developed for this study.

The observational sheet followed the structure of the tutorial and enabled the researcher to comment on the student responses to each task question and on software design. During the stimulated recall interviewing, the observational sheet allowed the researcher to emphasize the questions and elucidate the episodes in which the student had most difficulties while performing the task. Some examples of questions a student was asked are:

How would you describe the way you formulated the answer? (Could you describe how you arrived at the answer.)

What steps did you go through when deciding on the answer?

How would you describe the benefits, if any, on the information given during the tutorial (representation / feedback / glossary / added hints etc.)?

In the data administration process the participants were coded by given pseudonyms. The interviews were transcribed verbatim from the videotapes. That allowed the researcher to gain additional insights and make additional notes. In cases the students

worked in pairs, from the combined videotapes that showed the task performance, the student-student conversations were also transcribed. The conventions suggested by French (1989) have been mostly employed in transcriptions of these interviews. All the transcripts were hand written in a book by the researcher.

The filled observational sheets were used in conjunction with the interview transcripts and the transcripts of students' conversation while performing the task (if working in groups) and the observations of tapes (the task performance and the interview) in the data analysis process (see Appendix 4 for a copy of the interview transcript and the corresponding observational sheet).

7.3.3. Analysis of Student Interaction with the Tutorial

The step-by-step analytical process such as employed in Study One (Chapter 6) was employed in the data analysis of this study. To identify themes which describe student interaction with this in-house computer-based stereochemistry tutorial, the accounts of one student are compared with the accounts of other students, therefore, the elements of the constant comparative method have been employed as well (Merriam, 1998).

The analysis was based upon the aspects addressed by the research questions.

(i) Step 1 - Student Use of the Tutorial

This step of the analysis aimed to answer the research question 2a. In the first step, the analysis of the first set of data (interview transcript, observational sheet notes, observing of the tapes) ended with the first list of grouped items (insights) of comments, terms and notes, together with the individual student responses to any of the listed items. The process was repeated with the next set of data and the two researcher's lists were compared. As more and more sets of data were analysed the insights from the lists became more obvious.

After all individual lists were compared and merged this step of the analysis resulted in the final list of items that emerged from the student interaction with the stereochemistry tutorial. Table 7.4. shows the final list of items, derived from the analysis of student interaction with the tutorial.

Table 7.4. Final list of items for the student interaction with the stereochemistry tutorial.

Final list of items /regularities	
Structural isomers	<i>Cis-trans</i> isomers, ring plane
Stereoisomers	Q 2a) problems
Conformational isomers	Colour
Configurational isomers	Simplicity
Enantiomers	Familiarity
Diastereomers	Processes:
Stereocentre	- counting atoms
Ball and stick models	- looking down C-C bond
Rotation of molecules	- group/atom's arrangement around C-C single bond
Enlarging of molecules	- looking for a stereocentre
Skeletal structures	- looking for double bonds
Q1-Q3 progress	- group/atom's arrangement about C=C double bond/ring plane
Use of glossary	- rotation to get mirror images
Intro Q3	- analysis of wedge, dashed lines
Hints	- looking for similarity
Feedback	- system elimination
Bond rotation	- guessing
<i>Cis-trans</i> isomers, double bond	

Pavlinic, 1998

Similarly as described in Study One, some of the items listed in Table 7.4. were concept related (for example, different types of isomerism), while the others, such as the use of ball and stick models and skeletal structures were related to the tutorial design (for more detailed description of the step-by-step process see Chapter 6, section 6.5.3. Analysis, (i) Step-by-step process, Steps 1-2).

Finally, the groups of insights from all sets of data were reanalysed simultaneously and organised into themes which described the ways students interacted with this computer-based stereochemistry tutorial. In this step of the analysis the individual student responses were merged for a more general conclusion. Also, student interaction with the tutorial assumed that both the concept related and the software related insights were integrated.

Therefore, the analysis of student interaction with the tutorial was based upon the whole content and involved the combination of both the structure of the tutorial and the

identifying of the characteristic software features that provided the student with different options, such as the type of interaction or different representations for organic compounds.

The contribution of each theme was assessed and named from students' discourse in which they highlighted a particular aspect of the software design or the way they went about a particular task (Merriam, 1998, pp.182-183). For example, the theme colour emerged when the participants talked about the red coloured oxygen.

(ii) Step 2 - Student Achievement of Intended Learning Outcomes

The second step of the analysis aimed to answer the research question 2b. It involved the selection of target learning objectives when interacting with the stereochemistry tutorial and the evaluation of how well students achieved these objectives.

The list of the target objectives included different isomer types/concepts that were repeatedly addressed in the tutorial from Exercise One to Exercise Three (structural isomers, stereoisomers, stereocentre, conformational isomers, enantiomers and diastereomers).

In addition, from the list of the objectives that are clearly stated in Part 6 of the study guide and given in Table 7.1., the following target objectives were selected:

- Describe the difference between stereoisomers and structural isomers.
- Describe the difference between conformational and configurational isomers.
- Define enantiomers and diastereomers and explain the difference between the two pairs of isomers.

These three task objectives, added from Table 7.1. (i.e. from Study guide), were classified as more challenging objectives, because not only a description of one particular isomer type/concept but also a comparison with the other isomer type and the identification of the differences between the two were required.

General thinking strategies that students used for problem solving in stereochemistry, that this study identified, were classified according to the isomer type/concept (target objective) being investigated. Table.7.5. shows the results obtained from the set of data collected from one participant.

Table 7.5. Thinking strategies employed and the responses collected from Amy in problem solving tasks of the tutorial

Isomer type	Strategy used	Evidence in student description
Structural Isomers	Counting of atoms	".. one, two, three .." [student-student conversation] " ..ten.. sixteen .. so this one is twenty, should have the number of atoms, Ok, so there is no number two .." [Q2a, student-student conversation]
Conformational isomers	Looking down the C-C bond Counting of number of single C-C bonds and looking for rotation possible System elimination	[videotape evidence] " Rotation, um .. it's mostly on the single bonds, you can't get that on double bonds" [interview Q3c] " .. not enantiomers, not diastereomers, they are <i>cis-trans</i> isomers and should have a double bond, so must be different conformers" [Q1e]
Stereoisomers - Stereocentre	Analysis of connectivity, bonds Use of wedges and dashed lines Four different groups	" .. the same connectivity, the same bonds but different orientation .." ".. yeah, drawing .. this side is going back, this one forward .." "I found it quite easy to recognise it 'cause it just got four different groups around it."
Enantiomers	Looking for mirror images Looking for stereocentre and four different groups/atoms	" that's good, having like the mirror, down in the middle so you can easily see what they are .." (student-student conversation) ".. look for a stereocentre, carbon, hydrogen, alcohol group, methyl group, ethyl group ..[pointed on each of them with a mouse]"
Diastereomers	Looking for the group/atom's arrangement about a double bond /ring plane	" .. <i>cis-trans</i> isomers have double bond .. so, one stick on the bottom, two on the top .. this one has another way .." "Oh, we chosen 1&4 because they are <i>cis-trans</i> isomers. You see, at the top would be a ring, off the cycle you've got two sticks, but one stick [shows by hands] .. so what they've done, just swapped them over which makes them <i>cis-trans</i> isomers, it's got two different things on the end of it, so you got one that goes across double bond and one on the same side and this is <i>trans</i> configurational isomer .." (Q 2c - interview)
Difference between structural isomers and stereoisomers	Different group/atom's connectivity (arrangement) vs. the same connectivity but different group/atom's orientation Counting of atoms and system elimination	".. structural .. should have the same number of atoms, could be 3&4, could be another one, could be either 3&4 or, see back here 1&3 " [Q2a] ".. the same arrangement, it's just different orientation .." [Q2b]
Difference between conformational and configurational	Looking for a single C-C bond vs. double C=C bond and group/atom's arrangements	" .. conformational ..um. rotation on single bonds, they have no double bonds .."

isomers	group/atom's arrangements	“ Configurational are <i>cis-trans</i> isomers.” “.. different bonding, double bond , where is double bond? I think if you have double bond you should see, .., they are not diastereomers, they are <i>cis-trans</i> and have double bond ..” [Q1e]
Difference between enantiomers and diastereoisomers	Looking for stereocentre and four different groups/atoms vs. looking for double C=C bond	“ Diastereomers, ah, they are <i>cis-trans</i> isomers.”

Part 1.indd . 2002

The responses given by Amy were evaluated as achieved. The same approach of analysis was employed in the analysis of thinking strategies demonstrated by other participants. The student responses (learning outcomes) in which students talked only about similarities of structures (i. e. in solving Q2a problem of structural isomers of terpene molecules some participants elaborated their reasoning for solution 1&4 that “they looked similar”, admitted that they used guessing or did not provide an explanation in agreement with formal scientific explanation) were evaluated as not achieved.

The evaluation of how well students achieved these concept related learning objectives was named *Student achievement of intended learning outcomes*. The evaluation process and the classification of achievement involved the same criteria such as employed in Study One (e.g. agreement with formal scientific explanation and student's ability to solve a problem; see also Chapter 6). All individual participant responses to a particular objective that did not show clear evidence or were missing were classified as no data.

(iii) Step 3 – Factors that Affected Student Achievement of Intended Learning Outcomes

In addition to concept related objectives, the objectives related to the design employed in the stereochemistry tutorial, were also added:

- Use of skeletal structures in understanding stereoisomers.
- Use of interactive ball and stick models in understanding stereochemistry
- Navigation through tutorial, use of glossary / hints, feedback
- Student progress through the tutorial

This step of the analysis aimed to disclose how well the three major features employed in the tutorial design influenced the student interaction with the tutorial and therefore

student achievement of intended learning outcomes or the task objectives. This aim was set up by the research question 2c.

The three sub-themes of the theme *Factors that affected student achievement of intended learning outcomes* were all software based and were given as the three major features employed in the tutorial design (see section 7.1.2 which described the tutorial development and Table 7.2. which illustrated the main characteristics of the tutorial design).

The tutorial was made up to meet different student characteristics, for example the glossary with simple solving problems was available to meet students with different prior knowledge. For that reason, in the analysis the factors related to student characteristics were omitted.

The influence of the conceptual structure of the tutorial on student achievement of intended learning outcomes, in which the model of increasingly complex molecules was employed, was monitored and named *Effectiveness of model progression*.

The influence of multiple representations used in the tutorial (the skeletal structures and the interactive ball and stick models) on student achievement of intended learning outcomes, named *Effectiveness of representations*, was evaluated by students' ability to use these representations when solving stereochemistry problems.

Finally, the effectiveness of the navigation links on student achievement of intended learning outcomes was evaluated by monitoring the students' use of glossary and the hints available in Exercise Three, and this was named *Effectiveness of navigation to glossary and the use of hints*.

In this final step, the individual student responses that were recorded on the individual lists were taken into account. The reviewing of the video-tapes and the reanalysis of the observational sheets were found particularly useful in analysing the factors that affected student achievement of intended learning outcomes. The observational sheets contained information about the number of attempts a student used to reach the correct answer, for example x, x, ✓ means that the student reached the correct answer at the third attempt (initially, plus/minus (+/-) symbols were used) or about a student's visit to glossary. Furthermore, the observational sheets contained notes about student use of particular representations, for example if students counted atoms rotating the ball and stick models or using skeletal structures (there is videotape evidence in which the position of the

mouse arrow is recorded). Other researcher's notes were also considered. All the information from the observational sheets was combined with the student discourse and the themes identified in the first step.

This step of the analytical process, which involved the analysis of observational sheets, enabled the researcher to quantify student responses to different stereochemical concepts as well as student progress through the tutorial.

All completed observational sheets were analysed for the number of attempts used by individual/groups to solve any problem in an exercise. This allowed the researcher to identify stereochemical problems with which the students had most difficulties in the tutorial, what was the preferred representation used in the solving of particular types of stereoisomers and how the practice with problems involving simple molecules helped students in dealing with more complex molecules. Support for the results of this analysis was sought by reviewing of the videotapes showing the task performance and in student discourse from the interviews.

7.4. RESULTS

The results of the effectiveness of the design employed in the computer-based stereochemistry tutorial given below followed the research questions of Study Two. The first aspect addressed the student use of the tutorial, taken as a whole (Research Question 2a). Next, the value of the design employed in the tutorial was checked by the evaluation of how well the students achieved the selected learning objectives (Research Question 2b). Finally, the three main characteristics of the tutorial design were reanalysed as the factors influencing students in achieving the selected target objectives (Research Question 2c).

7.4.1. Students' Use of the Tutorial

The students' talk, action and choices when interacting with the computer-based stereochemistry tutorial led to the identification of six themes with respect to the way students used the tutorial.

(i) Manipulation of On-screen Models

Experiencing the 3D interactive ball and stick models on the screen was found by all

participants as a “new” way of representing organic molecules and something special this tutorial provided for them (Hawthorne effect). The comments about the on-screen ability of moving or rotating models were present in student discourse, from the first impression given to the description of the ways they approached a particular stereochemistry concept. Furthermore, the ability to rotate molecules and compare if two molecules are mirror images was described as particularly useful for identifying enantiomers.

In her very first response to the tutorial Tracy said:

It was good .. Specially when you see this, that you can rotate .. yeah .. rotate the molecules and see how they look like in a different ... from a different view .. sometimes it is very helpful because sometimes you just have this molecule, you can't see the hydrogen atoms itself. (Tracy)

Later on, she commented:

.. it's also good you can make them bigger, makes them look a lot more clear. .. (Tracy)

Other students also highlighted the importance of rotating or moving models:

... you can move the ball and stick one, cause, ..., you can see the plane, just see it and count the carbon and stuff, ..., you can move it and count hydrogens and stuff with the ball and stick model which is good. (Judy)

I think it was quite good. You can see the model three-dimensionally which is good .., you can rotate it, you can enlarge it .. (Amy)

The use of molecular models in grasping abstract chemical (Ingham & Gilbert, 1991; Laws, 1996) and particularly stereochemical (Baker, George, & Harding, 1998) concepts has been found to be helpful, as a hands-on approach with concrete, physical models encouraged students to think in terms of shapes of molecules and construct models on their own. Although this was not possible in the tutorial, the software allowed students to *rotate* on-screen 3D models and *observe* them from different views. This interactivity gave students the chance to investigate structures themselves, rather than just watching as in lectures:

... it's good when you've got to work out things like the shape of molecules and stuff like that, because you can turn on and have a look at the shape. (Judy)

The participants appreciated the on-screen manipulation with 3D ball and stick models, even those who preferred the skeletal structures to the on-screen ball and stick models.

Mick, for instance, commented on his inability to rotate skeletal structures as the only deficiency in the use of these representations:

You can't actually turn them around, can you? That's the only thing that is not so good about them but I found it easier to see the positions of double bonds so it comes at the little picture .. (Mick)

(ii) Multiple Representations

Apart from the 3D interactive models, students were also presented with 2D skeletal structures. The combination of different representations on the screen brought about the theme entitled 'Multiple representations'. Students talked about different aspects of the multiple representations available in the tutorial and these were introduced as different dimensions describing this theme.

Three different dimensions of the theme Multiple representations have been identified. First, students appreciated the ability to *move between different representations* allowing them to investigate a molecule using either one (2D or 3D) or both of them, as necessary: " .. you can move the ball and stick one, ... , but once you don't really need to move it - it's good to have the skeletal one." Switching between 2D and 3D representations as appropriate is an important feature of the professional chemist's approach to solving problems associated with molecular structure. Kelly commented favourably on having both kinds of representation available:

... having the ball and stick and the structural was good to see the relationship between them ... yeah ... (Kelly)

and described the use of ball and stick models as good to "see where the hydrogen were" or to "see what the shape was", but also highlighted how he is more familiar with the skeletal structures.

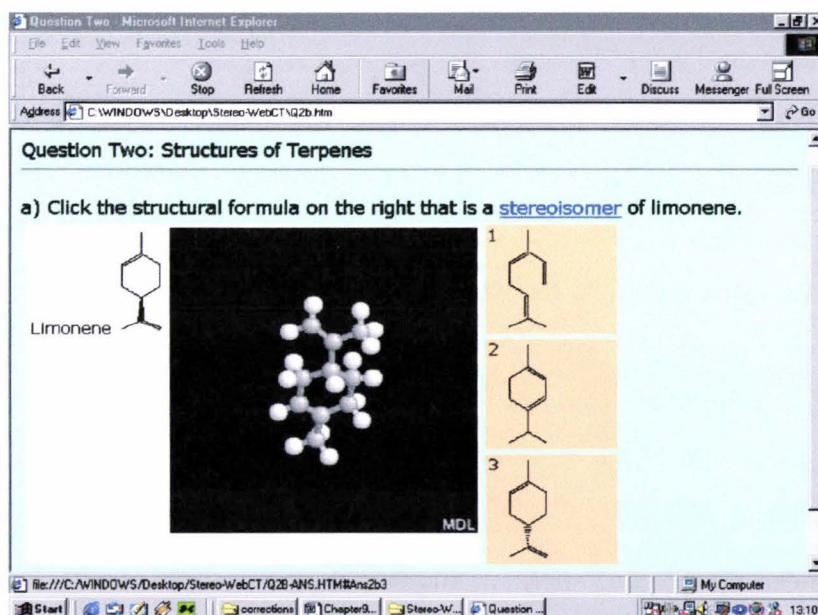
Another student described:

... you can move the ball and stick one, cause....you can see the plane, just see it and count the carbon and stuff, ..., you can move it and count hydrogens and stuff with the ball and stick model which is good, .. like put them next to each other, but if you don't really need to move them, [sawhorse and 3D of conformational isomers] it's good to have the skeletal one. It's pretty easy to see ..

Yeah, it was good having both representations, because you can, like, count of the carbons on the skeletal one and ..um...then go to the ball and stick and count the hydrogens on it." (Judy)

Offering the student more than one way of viewing molecules and the opportunity to select the one that better suits his/her view helps the student in developing the individual skill of 3D visualisation.

The aspect that relates to the use of multiple representations/models is a student's ability to switch from one representation/model to the other at a time of instruction or task performance. In-depth analysis of students' responses revealed that to some participants the problems of transition from one representation/model to another were still present while doing Exercise Two. These problems were revealed when students discussed the task exploring stereoisomers in Exercise Two, shown in Figure 7.2.



Stereochemistry tutorial, 1998

Figure 7.2. A copy of the screen showing the task of exploring stereoisomers in Exercise Two.

The participants described how they found it hard to compare the ball and stick model of one molecule with the skeletal structure of another. The interview episode with Den revealed that this student did not find it helpful that the ball and stick model was given only for one molecule and not for the other molecules on the screen.

Den: For this one here .. [in Study Two the task exploring structural isomers was Q2b] .. I was better off with drawings because there are no ball and stick models for the other ones so, .. I moved that one around the centre, obviously was not very much help if there was not something else to compare...

R: Were you wanting the ball and stick models for other molecules as well?

Den: For me, yes, .. there was nothing else to, there were no ball and stick models for the other .. like ... the options, for the choice I suppose .. so they didn't really help me ... comparing apples and bananas.

Second, an ability to *change the model display* in 3D ball and stick models gave students the chance to see and explore the same model using ball and stick or space filling representations. After experiencing interactive 3D on-screen models (often for the first time) students expressed their appreciation of recognising a “sort of true representation” (Tracy). Den commented:

.. you get them sort of like ball and stick models, but .. actually they're more like space filled models .. (Den)

and he responded to the space filling model: “that is better, that is sort of true representation”.

The third dimension of this theme describes the student response to being able to link to a written explanation of key terms and ideas (in which the role of language is added). The importance of understanding different languages of chemistry (verbal and nonverbal) and making connections between them (Lemke, 1994; 2002) was made possible by the *navigation* options in the tutorial. As shown earlier by the diagram in Table 7.2., the navigation links from the exercises to the glossary enabled students to associate the representation with its meaning, for instance.

Although all participants found the navigation easy, not all used the navigational option to the glossary. The positive responses of the participants who used the glossary were given in one way:

[went to glossy to check terms] .. It wasn't too much in depth, just a brief description and you could remember [what the stereoisomer is]. (Kelly)

or another:

.. but, having the glossary there with definitions was good ... (Mick)

During the interview Amy mentioned several times how she appreciated the possibility of going to the glossary (she and other students used the term notes). First she described how they (she performed the task working in pairs) tested navigation options available in tutorial:

We were just testing how the computer works, to see if you can go back to the notes and come back to the question. (Amy);

and then added:

The definitions were probably quite good ... you can go back to it, to see what it meant ... I found it quite handy. (Amy)

Later on, she discussed the tree diagram in the glossary that was designed to help students to navigate more easily through stereochemical concepts:

That's good. It's a very handy diagram. Dr Wright put it back on the screen at the lecture. You can refer to it and see like what kind of isomers they are and how they orient to one another .. (Amy)

(iii) Feedback/Hints

Two aspects of this theme were distinguished. One was the feedback that was available in each task of every exercise. The other aspect referred to the hints that were available only when dealing with the big prostaglandin molecule in Exercise Three.

During the interview while stimulated by watching the videotape of their task performance the participants commented on the **feedback** provided by the tutorial. Most participants' responses were positive, such as that of Judy:

It was good, it told you what was right or if you got it wrong .. yeah, it was like explaining rather than just saying something you gotta find the structural isomer of it .. so .. that was good. (Judy)

Different episodes of the interview suggested that the feedback in the tutorial assisted Tracy in constructing knowledge on her own and negotiating her knowledge with the formal chemistry explanation (Vygotsky's sociocultural perspective):

Good. When you have something wrong ... and it is explained what might be the reason .. It tells you, well, there is something else and have a look at this and this, maybe you can find out something there, ... and this was very helpful specially when you did something wrong and you don't know why ... you just said .. um .. what can be wrong ... it just tells you maybe you can go there and have a look at that.. (Tracy)

.. was good to see what I am doing wrong ... Because ... with sample with these rotating bonds I wasn't sure if these single bonds also could be rotating or not ... It was good to see what I did wrong at the end, where the bonds are and show you rotating on them ...(Tracy)

However, although pleased with most of the feedback given in Exercise One and Exercise Two, the feedback in Exercise Three did not challenge Den at all:

I think it was good ... when you were right it told you why you were right, ... but other times you got the answer without making you think about it .. Um, sometimes like ... one of them, there were four possible answers and there was one, two three or four [answer options to choose] ... and I picked three and it said there are more than three. It sort of told me an answer without making me think about it, .. like, go back and click four but it didn't make me think about why this was four. (Den)

The other aspect of this theme refers to the **hints** available only in Exercise Three, and this was revealed from the students' responses to the introductory page prior to Exercise Three and from the students' use of the hints when performing the tasks of Exercise Three. The introductory page to Exercise Three had an example of skeletal structure of a single organic molecule and was aimed at informing a student about the availability of the hints in the tasks of Exercise Three and the way the hints could be reached.

The analysis revealed that only two participants understood the instructions given in the page prior to Exercise Three and later used the hints available in Exercise Three. Three students misunderstood the message of the introductory page to Exercise Three (Tracy, Amy and Judy) and did not use hints at all. For example Tracy explored the structure at the introductory page to Exercise Three but did not use the hints later on:

It's nice to see that they tell you ... what it is and where it comes from and you can have a bit of a look at the molecule ... [but, she didn't use the hints later in question] (Tracy)

They told you what to do. But I didn't see the point in the bit in the box, um, with telling you that there are two hydrogens of ... if you didn't know that you couldn't do the rest of exercise we just did. If you click on it just says this is got a CH₃ group or CH₂ group. If they gonna do that, they should do that at Exercise One, because all others are based on that. It's a funny place to put it on the exercise. They should know where to have it or have it in the beginning. (Amy)

I didn't really see much relevance in that, but I probably didn't read it properly. I didn't really understand that it was supposed to be the introduction; I was, sort of, trying to work out, what was it doing. (Judy)

These students' responses suggested that the design of introductory page to Exercise Three failed to provide appropriate scaffolding to the students.

Some participants 'discovered' it by accident during the task performance and not from the introductory page:

Um ... wasn't very clear what we should be doing, but once you know, you can see how it helps in doing a question. (Kelly)

That was helpful ... but ... I think sort of when you pressed the hint it told you that you got the hint there rather than actually saying that would be a hint ... I knew that. I sort of understood that. When I came to rotation I wasn't quite so sure how it was going and the hint helped me. Yeah, it did ...it was not until I got through to the first question that I used the hint. I sort of started to understand how the hints worked more. (Mick)

When during the task performance Den clicked on the molecule by accident and got the hint he was surprised and explored it in more detail. However, it was only during the last task that he 'discovered' the hints (Question 3c was the last task of Exercise Three and of the whole tutorial at that time). During the stimulated recall interview Den explained:

I sort of forgot until now, forgot to click on the molecule to get a hint. (Den)

Finally, two of the students who used the hints made the comments:

Oh, .. it was easy to count and also it's good like that, written in that form, because it's a reminder that you need four ... four different groups and I often forgot that, when I read the text I often forgot that it was supposed to be four different groups cause I didn't see it. (Kate)

It was quite good, when you put it on the stereocentre it [cursor in a form of hand] told you it was a strereocentre. (Sue)

(iv) Use of Colour

The comments about the colour appeared on six lists made by the researcher during the analysis process. In some transcripts the colour was mentioned when students described the interaction with the ball and stick models on the screen.

Many students were talking about red-coloured oxygen or pointed at the screen with their finger during the student-student conversation when exploring enantiomers of C-4 alcohols (Exercise One).

For example:

You can rotate the molecules, you can see how they ... like swapped over easy, ... probably could also be seen on the line diagram but it gave you a chance to see it in another way. And, it's quite handy how you got the oxygen in different colour. That made a lot easier to recognise. (Amy)

Also, one student talked about the grey-white carbon-hydrogen frame when exploring terpene molecules (Exercise Two).

.. like, the carbon and the hydrogens, they are pretty much the same colour and sort of get a bit confused. (Judy)

The colour contributed to the students' emotional and verbal satisfaction with the feedback in Exercise Three as well, though the term '*colour*' was not used in the students' description. For example, the students' emotional satisfaction with the feedback, in which the red coloured symbols -C were inserted in the skeletal structures to highlight all stereocentre-carbons, was apparent. The other example refers to the students' responses on the feedback to the task which investigated conformational isomers in Exercise Three, in which the red colour was used for numbering and for emphasising all single carbon-carbon bonds that are free to rotate:

.. was good to see what I was doing wrong ... Because ... with the sample with these rotating bonds I wasn't sure if these single bonds also could be rotating or not ... It was good to see what I did wrong at the end. (Tracy)

It's good to have it ... The numbers on them show you where they are.. (Judy)

The influence of colour on student learning is well known. Shubbar (1990) for example, referred to an earlier study (Seddon & Shubbar, 1984) in which the use of multicoloured diagrams improved the student's ability to visualise rotation. In the present study, students described having differently coloured atoms (e.g. red for oxygen) as "quite handy" making the molecule easier to recognise or assisting them with orientation aspects, unlike the monochrome grey-white carbon-hydrogen frames of the more complex molecules which made the students confused. The students made no comments about assignment of a colour to an element.

(v) Simplicity

Data collected revealed that the use of 2D skeletal formulae was regarded as a simpler way of representing molecules. The theme Simplicity has been characterised by the use of 2D representations in three ways. Firstly, 2D symbolic representations are important when used to simplify the more *complex molecules*. In some situations the ability to on-screen rotate the 3D ball and stick molecules confused students because of the multitude of images that are generated "... there are so many different ways to turn them and sometimes you don't really know what are you looking at" (Judy).

Furthermore, 2D representations show the *type of bonds* explicitly:

I found it easier, probably those skeletal structures .. yeah .. I found it easier to

see the positions of double bonds. (Mick)

In conclusion, students described the use of skeletal formulae as “easier to see” or “clearer” when counting atoms or looking for double bonds:

I actually found it easier exploring the structural formulae ... because you can see them easier. I know that ball and sticks, like, give you all the atoms but ... those ones are, like, really clear. Ball and stick you can turn around, that's OK, but ... generally I found skeletal structures easier. (Sue)

Sometimes it's a lot clearer than the ball and stick models because the ball and stick hide each other .. (Amy)

Another related aspect, which was identified as a dimension of this theme, is a student *familiarity* with 2D representations given in the tutorial.

Most participants described both the 2D skeletal formulae and the 3D interactive on-screen ball and stick models as ‘new’ ways of representing organic molecules. However, most of the participants described how they felt more familiar with skeletal formulae (which are the type of symbolic representations), as the other symbolic ways of representing molecules (such as structural formulae) are the ways mostly used during their high school and in most other teaching resources (textbooks):

.. the structural we practiced because that's what has been used in exams and that sort of thing, .. maybe more familiar with the structural.. (Kelly)

Students who had mastered skeletal formulae found it “.. a lot easier to write, rather than using the one with hydrogens” (Amy). Skeletal structures were found much easier when analysing structural isomers and diastereoisomers. The former were more easily distinguished because students found using skeletal formulae an “.. easier way to count the atoms” due to “.. you get mixed up with the ball and stick model, you have to rotate it because you can't see properly and then you forget the numbers and all that” (Tracy). The latter is recognisable by the clear presentation of double bonds.

However, in solving problems using this kind of representation the participants had to interpret skeletal formulae. Amy described how she gained an understanding of this type of 2D representation:

First I got mixed up counting the carbons. If you are going to draw out hexane you draw five lines instead of six and stuff like that, but you get used to it and it's not as crowded as drawing hydrogens on it. It's quicker. (Amy)

For two others the problems still remained. One student described “.. the lines are

confusing and sometimes the double bonds just confuse me more ..” (Kate) or another “I am sometimes confused so I can never remember where the hydroxo group is on the end I can never remember whether carbon is on the end, on that stick as well” (Den).

(vi) Type of Isomerism

Finally, for the theme Type of isomerism the insights from different themes combined together were examined along with the different representations employed by the students in identifying types of isomerism. It appeared that the *preferred representation depended on the stereochemical concept* being tested and on the complexity of the molecules used to explore stereochemical concepts. Table 7.6. shows the common preferences for 2D or/and 3D representations in understanding a particular type of isomerism.

Table 7.6. Preferences for the use of 2D/3D representations in understanding types of isomerism.

Type of isomer being analysed	Representation	
	3D interactive models	Skeletal structures
Structural isomers	✓ for simple molecules	✓ for complex molecules, easier to count atoms
Enantiomers	✓ rotation possible, different colours for different atoms	
Diastereomers		✓ the position of double and single bonds are clearly represented
Conformational isomers		✓ the position of double and single bonds are clearly represented

Paylme, 1998

The summary of identified themes and dimensions of each theme, supported by examples from students’ talk is given in Table 7.7.

Table 7.7. Themes in the student use of the stereochemistry tutorial.

Theme	Dimensions of theme	Evidence in student talk
Manipulation of models	* Rotation, inversion and reflection of 3D models and enlarging. * Observation along different axes.	* “.. it’s good when you get to work out things like the shape of molecules..” * “.. see how they look like from different views.”
Multiple representation	* Ability to move between different representations. * Change of model display * Navigation options from model to meaning	* “.. you can move the ball and stick one, .. which is good, like putting them next to each other, but once you don’t really need to move them, it’s good to have the skeletal one, it’s pretty easy to see ..” * from ball and stick to space filling model * from Exercise to Glossary and back
Feedback/ Hints	* Feedback * Q3 –Intro * Use of hints	* “.. was good to see what I was doing wrong” * “I didn’t see the point in the bit in the box” * “It was quite good, it told you it was a stereocentre. “
Use of colour	* Different coloured atoms make the molecules easier to recognise.	* “.. and it’s quite handy how you got the oxygen in different colour, that makes it a lot easier to recognise.” or “.. like the carbons and the hydrogens are pretty much the same colour and sort of, get a bit confused.”
Simplicity	* For complex molecules, 2D skeletal formulae simplify. * 2D skeletal and structural formulae show the type of bond explicitly (3D models implicitly). * Familiarity For complex molecules, 2D skeletal formulae distinguish bonding sequence and are easier to interpret (familiar).	* “... there are so many different ways to turn them on and sometimes you don’t really know what are you looking at ...”(3D models) * “.. easier to see the positions of double bonds ..” or * “.. clear to see the actual bonding ..” * “... we practiced them [skeletal] because that’s what has been used in exams ...”
Type of isomerism	* Preferred representation depends on stereochemical concept.	* skeletal formulae for structural isomers (“.. easier to count atoms” as “.. the ball and sticks hide each other..”) or diastereomers (“..clear to see double bonds..”) and 3D models for enantiomers

Paylme, 1998

7.4.2. Student Achievement of Intended Learning Outcomes

When solving stereochemical problems students combine a number of themes that were described in the previous section (7.4.1.).

In the tutorial, students were asked to interpret the meanings of different stereochemical terms through problem solving exercises (Exercise One – Exercise Three); therefore the

connection between the two was required. A summary of student responses from which an assessment was made of how well they achieved the selected learning objectives is given in Table 7.8.

Table 7.8. Student achievement of intended learning outcomes (task objectives).

Task Objectives	Achievement / no. of students		
	Achieved	Not achieved	Not evaluated
Concepts related objectives			
• Describe structural isomers	8	1	1
• Describe stereoisomers	10	-	-
• Describe the difference between stereoisomers and structural isomers	1	5	4
• Describe conformational isomers	4	4	2
• Describe the difference between conformational and configurational isomers	2	5	3
• Define chirality and recognise the presence of stereocentre/s in molecules	8	-	2
• Define enantiomers	10	-	-
• Define diastereomers	4	5	1
• Explain the difference between enantiomers and diastereomers	5	1	4
Total number of responses	52	21	17

Out of the total number of evaluated responses shown in Table 7.8., 57.8 % were evaluated as achieved. Of nine of intended learning outcomes only four were achieved by the majority of the participants. Some objectives (for example describe stereoisomers and enantiomers) were mastered by all participants. However, for more challenging objectives (e.g. the difference between structural isomers and stereoisomers or the difference between conformational and configurational isomers) the clear evidence of achievement was shown by only a few students.

Although provided with the link to the glossary, half of the participants did not master the objective *define diastereomers*. In addition, just two participants achieved the objective *describe the difference between conformational and configurational isomers*. It might be that these objectives were not achieved because students were unfamiliar with the terms diastereomers or configurational isomers and for the reason that some students did not realise the glossary was available (described later).

Amy was very confident with these types of isomerism because each time she faced the problem dealing with diastereomers or configurational isomers she would visit the glossary and ‘translate’ them into the *cis-trans* isomers, the term known from high

school:

R: Why did you choose 1 and 4 for configurational isomers?

Amy: Oh, 1 and 4. Because, they are *cis-trans* isomers. If you see . at the top would be the aromatic ring [5C-ring].. off the side you've got two stick bits and one stick , .. so what they have done, they have swapped them over which makes them *cis-trans* isomers, because it's got two different things on the end of it, so you have got one that goes across double bond and one on the same side and this is *trans*, and this is *cis* configurational isomer, so..

7.4.3. Factors that Affected Student Achievement of Intended Learning Objectives

Three aspects of the software design that were considered in the tutorial design were identified as those that affected the students in achieving intended learning objectives. The results of the effectiveness of each aspect on student achievement of intended learning outcomes are given below.

(i) Effectiveness of Model Progression

As described in Section 7.1.2. the tutorial was designed so that increasing conceptual demands were made as successive stereochemistry problems were solved. These were set up to test stereochemistry concepts by using simple molecules of C4-alcohols (Exercise One), the more complex terpene molecules (Exercise Two) and the prostaglandin molecule (Exercise Three). Two different kinds of representations were used, skeletal structures and ball and stick models. All of the themes that were identified and described earlier (see Table 7.6.) contributed to the analysis of student progress through the tutorial as the complexity of the molecules increased. A number of the identified themes, given above (section 7.4.1.), indicated how students' preference for either one or another type of the representations given (skeletal structures or ball and stick models) depended on the type of isomerism being investigated and also depended on complexity of the organic molecule.

Therefore, two dimensions of the student conceptual progress through the tutorial were monitored:

- Concept/type of isomerism - complexity of a molecule relationship;
- Way of representing molecules per concept - complexity of a molecule

relationship.

The insights into the **relationship between the student ability to solve the particular stereochemical concept and the complexity of a molecule studied** were made by examining the number of attempts the students used to solve a particular stereochemistry concept while progressing through the tasks (from Exercise One to Exercise Three). Students' discourse, filled observational sheets and the videotapes were used as data sources. Individual observational sheets were reanalysed, compared with each other and combined.

Table 7.9. shows the student/group progress through the tutorial recorded as the number of attempts used to reach a correct solution per type of stereochemical concept tested. The number of attempts was derived from the observation sheet/interactive map recorded per each task performance. The number of analysed sheets is less than the total number of students (Table 7.9.) as some of students performed the tasks working in groups and, as described in Chapter 5, section 5.4. one student did only the glossary part of the tutorial (eight observational sheets were analysed, two groups of pairs; one student did the glossary only).

Table 7.9. The student/group progress through the tutorial recorded as number of attempts used to reach a correct solution per type of stereochemical concept tested.

Concept / Isomerism being investigated		No of sheets/No of attempts to solve a problem								
		Exercise One (C4-Alcohols)			Exercise Two (Terpenes)			Exercise Three* (Prostaglandin)		
		1 st	2 nd	>2	1 st	2 nd	>2	1 st	2 nd	>2
Structural Isomers	ball & stick	6	1	1	0	5	3			
	skeletal	7	0	1						
Enantiomers	ball & stick	5	1	2						
	skeletal				7	1	0			
Stereocentre		6	2	0				4	2	1
Conformational Isomers	ball & stick	5	2	1						
	skeletal							3	3	1
Diastereomers	double bond				4	1	3	4	2	1
	ring plane							2 [#]		
Stereoisomers					7	1	0			
Configurational					4	3	1			

*One individual has not done Exercise Three

[#] Additional question, was available for pairs and one individual

Pavlinic, 1998

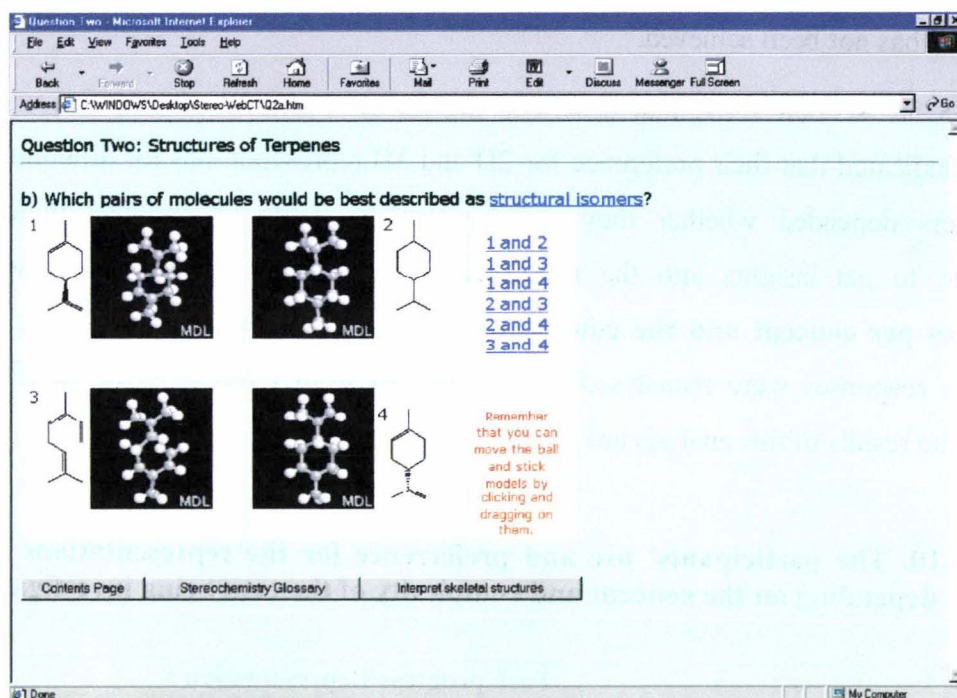
Although it did not matter if a student required more attempts so long as task was achieved, the change in the pattern in student responses when moving from Exercise One to Exercise Three was apparent. The figures in Table 7.9. show that the students' success in solving stereochemical problems dropped as they moved through the tutorial and as more challenging tasks with more complex molecules were tested for the same concepts. For instance, the majority of the students described the tasks in Exercise One easy and had chosen the correct solution in their first attempt when solving the problem of structural isomers of C-4 alcohols (6 of 8). However, in solving the problem of structural isomers of terpene molecules in Exercise Two and using the same way of representing organic compounds as done in Exercise One, it appeared that the students were much more challenged, with none of the participants succeeding in getting the right solution in their first attempt.

It appeared that the application of a concept, for example identifying structural isomers when combined with increasingly complex molecules became too challenging (even for the high achieving students). Students had difficulties in counting atoms, especially if molecules consisted of just C-H carbons on a gray-white ball and stick frame. Not being sure of how to interpret the skeletal structures made the task even more complex.

The participants discussed multiple aspects which caused them difficulties when dealing with the problem of identifying structural isomers of terpene molecules in Exercise Two. Although the ball and stick models were available too, most participants used the skeletal structures in solving this problem. Some participants indicated their problems in using skeletal structures (Den, Kate), others described how they got confused with the size of molecule and were 'lost' while counting atoms (Sue and Kelly). However, Amy described how she experienced this question:

It's hard to see them all on the page. When you get four on the page they are quite small, so when you enlarge them you don't really enlarge them very much [ball and stick models], I mean, the previous ones, there were only two of them [Exercise One, and also involved smaller molecules] you can enlarge and see very clearly .. I still find it a bit hard to see them. I used the ones on the sides to count atoms .. [skeletal structures]

Figure 7.3. shows the screen capture of the question Q2a.



Stereochemistry tutorial, 1998

Figure 7.3. The capture of the screen from Exercise Two in the tutorial showing the question which caused the participants the most difficulties.

Students were presented with four terpene molecules represented in two ways using the skeletal structures and the ball and stick models. In addition to the complex molecules the task required students to simultaneously compare structures one with another and select the pair that are structural isomers. Apart from the conceptual demands, the difficulties observed may have occurred due to this page design fault (e.g. graphics with a background that did not provide greater contrast). Amy commented that it was ‘hard to see them all on the page’ as ‘you got four of them’ and ‘the previous ones, there were only two of them’. A risk of page overloading, which refers to cognitive overloading, is often present in designing computer-based learning tasks. As Johnstone (1997) explains, quite often too much information causes the overloading of working memory and “students begin to fail when working space is overloaded” (p. 264). This is particularly applied in learning chemistry in which students have to deal simultaneously with the macro and “intangible” micro and symbolic chemistry languages (Johnstone, 1999, p. 46). In designing computer-based tasks, information overloading can be avoided by more appropriate chunking (less number of chunks available on the screen).

The difficulties showed by the participants in solving the problem of structural isomers of terpene molecules in Exercise Two indicated that the aimed student-software

interaction has not been achieved.

Table 7.5. in section 7.4.1. that described the themes of student interaction with the tutorial, indicated that their preference for 2D and 3D representations for different types of isomers depended whether they were exploring simple or complex molecules. However, to get insights into the **relationship between the way of representing molecules per concept and the complexity of a molecule studied**, the participants' interview responses were reanalysed as they moved from Exercises One to Exercise Three. The results of this analysis are given in Table 7.10.

Table 7.10. The participants' use and preference for the representations in the tutorial depending on the concept and complexity of the task being investigated.

Isomerism/Concept	Task progress/Representation *					
	Exercise One (C4-Alcohols)		Exercise Two (Terpenes)		Exercise Three (Prostaglandin)	
	skeletal	ball & stick	skeletal	ball & stick	skeletal	ball & stick
Structural	✓	✓	✓✓	✓		
Stereoisomers			✓			
Stereocentre	✓				✓	
Conformational		✓			✓	
Configurational			✓✓	✓		
Diastereomers			✓✓			
Enantiomers		✓✓	✓		✓	

Pavlinic, 1998

* ✓ used
 ✓✓ preferred

The previous section, which analysed the ways students used the tutorial, already discussed the student preference for symbolic skeletal structures when considering more complex molecules.

3D representations helped students when discerning the shape of the molecule, for instance: “.. because you can see where the hydrogens are” (Kelly), but not if the counting of atoms was required: “.. the balls and sticks hide each other” (Amy) or “.. was a bit confusing because all the hydrogens were getting in the way a little bit. They sort of obscure the picture” (Den). In addition, rotating the ball and stick model when investigating more complex molecules caused confusion because of “ ... so many different ways to turn them on and sometimes you don't really know what are you looking at ..”. Students found the skeletal structures “easier to count atoms” and “clear to see actual bonding”.

(ii) Effectiveness of Representations

Students found the use of the ball and stick models useful when exploring simple molecules and particularly in investigating enantiomers. However, when dealing with the problems that involve complex molecules, the preference shifted to the use of 'more simple and more familiar' skeletal structures.

However, both the student discourse (either from the interview or the student-student conversation) and the tape observing did not provide enough evidence of how well all students understood this type of representation (i.e. what the skeletal structures represented). Although the scaffolding was provided in the feedback of the tutorial (the link Interpret the structure) not all participants used the help provided.

As described earlier (section 7.4.1. Student Use of Tutorial, theme Simplicity, dimension Familiarity), two participants clearly indicated their problems in understanding skeletal structures, Kate who found “.. the lines are confusing ..” or Den who was “ sometimes confused so I can never remember where the hydroxo group is on the end, I can never remember whether carbon is on the end, on that stick as well.” The understanding of the representation used affected the student achievement of intended learning objectives.

It might be that more practice was needed in using skeletal structures before commencing the tasks that explored concepts of stereochemistry. Amy's quote (given before in section 7.4.1. (v) Simplicity) indicates how, before reaching the stage of confidence, she also initially had problems similar to those described by Kate in the paragraph above in interpreting skeletal structures.

The lack of confidence in interpreting skeletal structures became more sensitive in problems involving complex molecules. Students have not reported problems in using either ball and stick models or skeletal structures in Exercise One (C4 Alcohols); they expressed their preference for skeletal structures. As discussed earlier students faced difficulties in transition from simple to complex molecules and the problems using skeletal structures were emphasised in tasks with complex molecules (Exercise Two and Exercise Three).

The evaluation of data collected from combined videotapes and students' discourse in which they described the ways they solved problems using either skeletal structures or ball and stick models was used in the analysis (e.g. when students counted atoms using

skeletal structures or when Amy, solving the problem involving enantiomers and the ball and stick on-screen models (Q1d) explained: “They are mirror images, look here is a stereocentre, carbon, hydrogen, alcohol group, methyl group, ethyl group ..”). Table 7.11. shows the summary of student ability to use the two representations given in the tutorial in problem solving of stereochemistry.

Table 7.11. Student use of ball and stick models and skeletal structures in the tutorial.

Tutorial Design Related Objectives	Ability/ No. of students		
	Able	Not able	No data
• Use of skeletal structures	5	3	2
• Use of interactive ball and stick models	6	2	2

Pavlinic, 1998

The difficulties the participants showed in their use of the representations in the tutorial indicated that the aimed student-software interaction has not been achieved.

(iii) Effectiveness of Navigation to Glossary and the Use of Hints

Table 7.12. shows the student use of glossary and hints. While hints were available only in Exercise Three, glossary was available throughout the tutorial, from Exercise One to Exercise Three.

Table 7.12. Student use of the glossary and the hints in the tutorial.

Tutorial Design Related Objectives	No. of students		
	Used	Not realised	No data
• Use of glossary			
▪ Exercise One	3		
▪ Exercise Two	5		
▪ Exercise Three	1		
Total	7	2	1
• Use of hints			
▪ Introductory page + hints	2	2	
▪ ‘Discovered’ hints by accident	2		
▪ Misunderstood the introductory page		3	
Total	4	5	1

Pavlinic, 1998

Out of eleven, one participant explored the glossary part only and has not done the exercises (elaborated in Chapter 5, section 5.4.). Two participants did not realise that the glossary was available. The episode from the interview transcript with Den reveals:

R: You didn't use the link to the glossary, to refresh the meanings of different terms

Den: Oh no, I didn't realise that that was there. ..

I couldn't actually remember what diastereomer meant so I, sort of, guessed that one. I was looking around for a help ..

R: yeah, it seems like you were trying to find out some additional information [videotape]

Den: Oh yeah, .. I was looking around to see if I could get any, sort of, clues .. to find anything ..

But, no, .. I can look at it now, it's very obvious, but .. [nods with head]

Those who used the glossary described its availability very useful:

I liked the way that when you did the exercise, you could go back to the notes [glossary], like go back and have a look at them Oh, OK, you knew what it was talking about, it was good, ..., just the way you can go back ..(Judy)

Most participants described the problems in Exercise One as easy and only three students visited the glossary. Exercise Two involved more complex molecules compared to those given in Exercise One, so students faced more difficulties in solving stereochemical problems in Exercise Two. The results in Table 7.12. show that only five students (two pairs and one individual) visited the glossary when dealing with the problems in Exercise Two. Because the results of student progress through the tutorial illustrated how all participants failed to solve the problem of structural isomers of terpene molecules (Q2a) at first attempt, it was expected that more students would try to seek help. It was expected that the number of students who turned to the glossary would decrease in Exercise Three because of the on-hand hints that were available in this exercise which might have been more helpful.

However, the results of the student use of hints emerged as a surprise. The results showed that only four students realised that the hints were available and used them in Exercise Three (two individuals and one pair). Only two students understood the introductory page to Question Three and used hints as was initially intended, two others 'discovered' the hints by accident.

It was revealed that from those who did not realise that hints were available, three participants misunderstood the message aimed by the introductory page prior to Question Three (see students' quotes in section 7.4.1., (iii) Feedback/Hints).

The difficulties the participants showed in understanding of the instruction given in the tutorial indicated that the aimed student-software interaction has not been achieved.

7.5. DISCUSSION

In answering the main Research Question 2:

How do students interact with an in-house authored computer-based tutorial of chemical concept – centred design? -

firstly, the student-tutorial interaction was described by identifying the major themes that characterised the features of the tutorial design as experienced by the participants; secondly, the interaction was evaluated as student achievement of intended learning outcomes (which were content-related objectives) and thirdly the effectiveness of three major features of the tutorial design (tutorial-design related objectives) that influenced student achievement were described.

The tutorial influenced both students' cognitive (what they learnt) and affective (how they felt) dimensions. The themes that described how students described different features involve the contribution of and combination of both. One example is the theme Use of colour, in which 'the red-coloured oxygen' affected students' cognitive processes in a different way compared to the one by grey-white carbon-hydrogen frame. Although the achievement of the intended learning outcomes refers to cognitive dimension, factors that influenced the student's achievement involved the affective dimension too.

Different factors contribute to the students' interaction with the in-house authored stereochemistry computer-based tutorial. Students appreciated the opportunities provided to on-screen interact with the 3D ball and stick models, and some described that this kind of representation shows "what the molecule looks like". Students appreciated being able to use the 2D skeletal structures and 3D interactive ball and stick models, and having the option of selecting the representation that better suited the type of isomers being displayed.

Addressing the role of representations in teaching and learning chemistry Bodner and Domin (1998) pointed out that students are unlikely to spontaneously switch from one kind of representation to another. The authors found that successful problem solvers constructed significantly more representations while solving a problem than those who

were not successful. Bodner and Domin suggested that an important way to help students to become better problem solvers was to encourage them to make use of as many different representations as they could.

This tutorial aimed at encouraging students to practice the use of different representations in solving stereochemical problems. Although schools use structural formulae and often use concrete molecular models, the two representations used in the tutorial, 2D-skeletal structures and the on-screen use of interactive 3D-molecular ball and stick models, were experienced as ‘new’ representations by all participants. Some students complained of not having the hydrogens when counting the atoms on skeletal formulae, others showed difficulties in the transition from one representation/model to another. To confirm these insights, more research was needed and these insights will be examined further in the studies that follow.

Most students progressed through Exercise One with no or just a few difficulties. These findings were confirmed by the subsequent interviews in which most of students described Exercise One as easy to follow. However, the students’ success when solving stereochemical problems involving simple molecules (C4-alcohols) does not guarantee the same success if they have to deal with more complex molecules. Difficulties arose when students faced the more complex terpene molecules in Exercise Two. All students failed to identify structural isomers in their first attempt, despite being given both the skeletal structures and ball and stick models. The identified confusion was attributed to several factors such as not knowing how to interpret skeletal structure (hydrogens are not shown), finding the use of ball and stick models unsuitable for counting atoms in more complex molecules (problems with counting and rotating of the model, a white-grey C-H frame, double bonds not shown etc.), page overloading or just failing to achieve conceptual understanding of what structural isomers are when given together with other isomer types (the objective of differences between structural isomers and stereoisomers). For example the meaning of structural isomers was not specifically tested in Exercise One. The participants failed in the task exploring structural isomers of terpenes (Exercise Two) for different reasons, either because they were not able to use the skeletal structures or for example, because they were confused with the size of molecules. Some participants discussed their own difficulties highlighting the contribution of one factor (e.g. Kate about her problems in understanding skeletal structures or Amy about page overloading). It is most likely that several aspects

together contributed in student failing, and the contribution of each aspect differed for different students.

The representations preferred depended on the type of isomerism being tested as well as the complexity of the molecule displayed. For the simple molecules given in Exercise One, ball and stick models were preferred when investigating enantiomers; no preference was reported for other types of isomerism. However, the skeletal structures were preferred for identifying isomers of more complex molecules (Exercise Two, Exercise Three). Having both kinds of representations available through adaptive feedback (Exercise One and Two) was welcomed regardless of how effectively they were used.

The positive students' responses to the feedback were shown from Exercise One to Exercise Three. In Exercise Three, which explored the stereochemistry of a prostaglandin molecule, an additional help was offered to the students through the hints available on the computer screen. The instruction of how to use hints was given in the introductory page to Exercise Three. However, it appeared that only four students understood the instruction of the introductory page and used the hints available in Exercise Three. All other participants either did not use the hints or used them only after they accidentally "discovered" them. Those who got the message used them a lot and described that the hints enabled them to easily solve stereochemistry tasks of the complex prostaglandin molecule. In addition, apart from not using the hints available in Exercise Three, the results also revealed that not all participants realised that they had an option of the navigation to the glossary. This indicated that the aim of the instruction about availability of glossary or hints, that was supposed to help the students in achieving the intended learning objectives, has not been achieved

The results of student achievement of intended learning objectives showed that 57.8 % of students' responses were evaluated as achieved.

The concept related task objectives and the evaluation of how well students achieved these objectives might be an indication of both student learning and the effectiveness of the software design. In addition to the evaluation of student achievement of intended learning outcomes, in this study students talked about learning other than what was specified in the list of objectives for this study. Den clearly described that he learnt "which bonds could be rotated" and "that the stereocentre can be in a ring". Also, there were other chemistry related matters that students gained from the tutorial. Tracy

described how she learnt how “molecules can have 3D structures”, while Mick apart from “I understand the rotation more now, the double bonds cannot be rotated, they are fixed ..” talked about learning how to use this kind of software. Although those aspects were covered by the objectives given in the study guide (see Table 7.1.), they were not evaluated in this study.

Therefore, it is possible that the other kinds of student learning that might have taken place during the student use of the tutorial have stayed hidden by the evaluation of student achievement of the selected learning objectives only (limitations of the study).

Apart from the complexity of molecules, the student understanding of the representations given, being able to navigate to the glossary and the use of the hints available, were assigned as the factors influencing students in achieving the selected learning objectives.

With the increasing complexity of the molecule, the use of symbolic representations such as structural formulae simplifies and highlights the characteristic features of the compound. Although at high school skeletal formulae are not in the Bursary prescription, the other symbolic ways using structural formulae have been used in schools, so the skeletal structures as a symbolic way of representing molecules appeared easier to use by the students. However, the students described the problems when counting of atoms was involved, or in interpreting the end-stick in skeletal structures (Exercise Two), indicating their inability to effectively apply this kind of representation in solving stereochemical problems.

This is a message to the lecturers, teachers and educators who use skeletal structures in their teaching and expect their students to understand them in the way that they do.

The second message relates to the use of simple and complex organic molecules in teaching stereochemistry. Quite often in exams, students have to deal with problems involving more complex molecules compared with those given in lectures. The confidence in dealing with problems involving simple molecules does not guarantee that the concepts can be applied in solving problems involving complex molecules. Testing the students' ability to solve a problem regardless of the molecule given in the problem is used as a test of the students' understanding of stereochemistry. In order to develop student understanding of stereochemistry in a way that students will show confidence in solving problems involving complex molecules, it is suggested that

students should get more practice with the problems involving complex molecules, such as with those provided by the tutorial.

The third message to educators and software developers is that the effect of any on-screen instruction must be tested by the students or those subjects at whom the instruction is aimed. Good on-screen information means that it should be clearly understood by the participants themselves. The ways students construct knowledge from the instruction provided to them inform about whether the instruction is effective or not. The method employed for data collection and analysis in this study was found to be an efficient way in revealing critical aspects of student-software interaction and particularly the ways the on-screen instruction given was received by their users – students. The on-screen instruction about navigation to the glossary and about the use of hints, both not understood by all participants as intended, became the target for attention when doing amendments in the tutorial and the research in Study Four.

The in-house authored tutorial has an advantage when compared with the commercial software because it opens up the possibility for making amendments in the tutorial. Therefore, not only can the tutorial be designed to follow the course requirements, but it also can be amended so the ways the instruction is given can be easily changed, or the aspects that have not been addressed before can be added. The insights that were identified from students' responses in this study, particularly those which indicated that the aimed student-software interaction had not been achieved, became targets for the revision of the tutorial in the study that follows.

7.6. CONCLUSIONS

The results of this study suggest that the combination of software features like colour, 3D shape and interactivity are powerful when refining ideas about the more complex concepts in stereochemistry (such as recognising enantiomers). The 3D interactive on-screen models and colourful molecular images available on computer enabled the students to practise the use of different representations, provided them with the opportunity to integrate 2D symbolic and 3D microscopic levels of understanding and enabled them to select the representation that for them best suited the problem. On a given problem students, of course, brought together a number of factors to get a solution and achieve the selected learning objectives.

The findings also suggest that multiple, 2D and 3D representations, with the possibility of moving between them depending on the aspect or type of isomerism being analysed, are useful and desirable for helping students learn stereochemistry.

Positive responses were expressed about the nonlinear task design (with the adaptive feedback provided). The link to glossary and the hints available in Exercise Three have not been used as was initially intended so amendments should be made (e.g. in the introductory page to Exercise Three) to make the introduction and the intended message clearer to the users.

Most of the participants started with the exercises, visiting the glossary as needed. However, some of them chose the glossary first. The navigation options and particularly the possibility of checking terms (which have to be learned as a part of concept) if ‘.. mixed up’ were very well received and frequently used.

Further analysis in which the student success in solving stereochemical concepts was analysed through the complexity of molecules in the tasks, showed how the stereochemistry concepts were rechallenged in solving problems with increased complexity of the molecules. All the previously identified and discussed themes are emphasised and became more selective when the conceptual demands (complexity of molecules) were increased. For example, simplicity and clarity of 2D representations over the 3D rotating models, the role of the colour when manipulating with ball and stick models, or partial understanding of any particular representations (in counting the number of atoms for instance) influenced student choice and therefore their success in any of the problem-solving tasks undertaken.

Tutorial design in which stereochemical concepts were tested using more complex organic molecules, navigation options to the glossary, hints available and the adaptive feedback employed, created the student - task engagement that provided the students with opportunities that made learning possible. 57 % of the participants achieved the intended learning outcomes, but apart from that the students described how they widened their knowledge by constructing new knowledge about stereochemical concepts. Comments such as given by Den or Tracy during the stimulated recall interviewing confirm that the tutorial assisted the students in constructing new knowledge:

I wasn't quite sure like if the stereocentre could be in a ring ... This one took me longer to figure it out with the hand, but once I had it.... like 'the hand' I

wasn't sure which bonds could rotate and which couldn't.. I clicked on probably half of the bonds or more than half of the bonds and got an idea which ones could rotate and which ones couldn't. (Den)

This is the first time that I saw the three dimensional part of molecules and all that .. we never did this 3D structures of the molecule [at school] ..

.. I think I never really thought about how they could have a 3D structure. Maybe that's why I have some problems with the image of how they really look like , because I was never taught that.. (Tracy)

When asked how they felt about the tutorial, very positive responses were given. One student described disappointment when finishing the tasks: "I was disappointed actually because when I finished that one I was ready to go and there were no more questions" (Den).

The students' responses, which indicated that the aimed student-software interaction had not been achieved, will be considered in the tutorial revision, later in the study that follows (Study Four).

8. STUDENTS' CONCEPTIONS UNDERPINNING THEIR UNDERSTANDING OF STEREOCHEMISTRY – STUDY THREE

One of the major developments in the field of science education in the 1980s was the recognition of the importance of students' prior conceptions. A number of articles identified these in different science disciplines and topics. In general:

- Students' conceptions were described as often being inconsistent with the scientific concepts the students were to learn in a science course and also described as sometimes being highly resistant to change (Driver, 1995; Pressley & McCormick, 1995). The findings of Study One of this thesis have shown that first year chemistry undergraduates vary in their prior knowledge about the concepts being addressed by the commercial software. Some students had inadequate prior knowledge to follow the pace of the tasks intended either by the software designers and/or course coordinator. Some students' conceptions were inconsistent with concepts defined by the scientific community.
- Ausubel (1968) who regarded students' prior knowledge as the most important single factor influencing learning, indicated that teachers should ascertain students' prior knowledge and teach accordingly. The insights from Study Two suggested that students might show understanding of the representation used differently from the intention of the instructor who employed it in the task (familiarity with skeletal structures, but not necessarily the ability to use them in solving problems).
- There are many CAI tasks designed for drill and practice. However, according to Lower (2000) most CAI tasks are being designed to follow the constructivist ideas. Constructivism as a learning theory is based upon students' prior conceptions (Biggs, 1999; Driver, 1995; Driver et al., 1994) or is a theory developed to back the prior conception movement (Tsapalis, 2001b). According to Kearney and Treagust (1999) "The elucidation on student ideas is central to any teaching approach informed by constructivism" (p. 2). Matthews (1995) argued that this is an essence of any good teaching and not an innovation advocated by

constructivism alone.

The initial aim of the tutorial (Study Two, Chapter 7) was to overcome some of the issues raised in Study One. The tutorial was designed in consultation with the staff teaching the course, rather than with the students taking the course. Therefore, the tutorial written for Study Two attempted to address in part the issue of different prior knowledge by providing navigation to glossary with background information as well as helpful feedback. Although the tutorial was developed in line with constructivist ideas, it was decided to undertake the examination of student conceptions to see how closely they matched the design of the tutorial. Therefore, Study Three aimed to investigate student conceptions, important in understanding stereochemistry and to check if the tutorial addressed these students' conceptions. It was planned that the findings of this study would be used in the revision of the stereochemistry tutorial (designed in Study Two) if necessary.

There are few examples of the use of research into students' conceptions as a means of designing CAI, particularly in chemistry. However, it is worth mentioning Laurillard (as cited in Ramsden, 1987) who described how research into students' conceptions was used as a means of designing simulation programs in the area of computer-assisted learning in science and engineering.

8.1. RESEARCH QUESTIONS

In the light of the main Research Question 3 as stated in Chapter 4, section 4.4.

What relevant conceptual knowledge and approach to learning do students bring to the computer-based tutorial?

and in order to revise the computer-based stereochemistry tutorial, students' conceptions related to their understanding of stereochemistry have been investigated.

The complementary Research Questions addressed in this study were:

- 3 a) How do students approach visualisation of molecules?
- 3 b) How do students relate their representations of a molecule to a macroscopic sample of the substance?
- 3 c) In what ways do students conceptualise each isomer type?

The stereochemistry tutorial in Study Two was designed to address the issue of how students visualise molecules. Therefore the Research Questions 3a and 3c are closely related to the issues addressed by the tutorial. Although the issue of the microscopic/macrosopic transition was not addressed in the tutorial, the research literature into learning of chemistry also raises the microscopic/macrosopic issue. Since there are no data on first year university students about microscopic/macrosopic transition, the decision was made to investigate it along with the microscopic/symbolic issue. For that reason, the Research Question 3b was added.

8.2. SETTING OF THE STUDY

Phenomenography was selected to be employed in this study. Phenomenography had already been used in exploring the ways students conceptualise chemical phenomena. Renström, Andersson and Marton (1990) employed phenomenography for an in-depth analysis of students' conceptions of matter. Strömdal, Tullberg and Lybeck (1994) explored students' conceptions of 1 mol, while Ebenezer and Erickson (1996) investigated chemistry students' conceptions of solubility. Davies Burns (1997) explored student conceptions of atomic structure and bonding. The reported results in all of the studies were descriptive; also some educational implications in the teaching of chemistry were suggested. However, the reports of the studies mentioned above referred to research with high school participants, not undergraduates.

Six participants (two chemistry professors, one senior lecturer, one scientist, one student/laboratory technician and one high school student) were involved in the preliminary exploratory interviews (see Entwistle & Marton, 1994, for a similar approach). These preliminary interviews were used to develop an appropriate interviewing style and to refine the interview questions. The preliminary interviews were not considered in the analysis process.

8.2.1. Students and Sampling

This study was carried out during the first semester in 1999. It focussed on the first year undergraduates enrolled in the organic chemistry course Chemistry I(a) at Massey University, New Zealand. The paper covers organic and physical chemistry topics and was taken by about 300 students who mostly entered the university straight from high school. However, the data collected (in consent form a student was asked to fill a gap

informing about his/her chemistry background) showed that the participants in this study differed in their chemistry background (see Appendix 5 (a) List of the participants in Study Three).

The number and characteristics of participants selected for the study were based upon purposeful sampling and the phenomenographical approach taken in this study. Redundancy (Lincoln & Guba as cited in Merriam, 1998, p. 64) was reached by twenty five volunteers of mixed gender who participated in the study.

Students enrolled in the first year Chemistry I(a) course at Massey University in 1999, were grouped in different streams to attend laboratory classes (not by alphabetical order but depending on the other papers in which they were enrolled). To sample participants across the whole class, the researcher visited seven different laboratory streams out of a total of nine, introduced herself and the study, supplied an information sheet and asked for volunteers. The two laboratory streams that were excluded were the streams that were running at the same time as the researcher ran her laboratory classes (two laboratory areas enabled the running of parallel laboratory classes) and one of the streams that was running at night (6.00 p.m. – 9.00 p.m.). In addition, the two streams were excluded because the appropriate number of the participants was already achieved. The same number of male and female participants and with different chemistry backgrounds (7th form, 6th form and below) were the criteria used in the selection. To get approximately equal numbers of males and females, a laboratory class with more males was chosen for further selections, seeing more females had already agreed to participate. Table 8.1. shows the characteristics of the participants employed in Study Three.

Table 8.1. Participants in Study Three.

Criteria/variables		Student proportion	
		Number	%
Gender	Females (F)	12	48
	Males (M)	13	52
Chemistry Background*	Form 7 and Bursary	8F and 9M	68
	Form 6 and Form 5**	4F and 4M	32

* Form 7 - final year of high school (17-18 years old)

** Two F and three M finished high school three or more years ago

Before an interview started, the invited participants were given additional information to read and a consent form to sign, both approved by the Massey University Human Ethics Committee (MUHEC). The tape recorder was placed in front of the student so she/he was able to stop the recording at any time during the interviewing process.

8.2.2. Techniques in Data Collection

(i) Phenomenography

(a) Interviews

The aims of the study were to find out the ways in which students visualise molecules, relate a 'real', macroscopic sample of the substance to their visualisation and also conceptualise different isomer types. For this reason, a pencil and a sheet of paper, a ball and stick modelling kit, a bottle labelled 2-butanol filled with a colourless liquid and a Periodic Table were available to students during the interview.

Step 1 – In-mind visualisation

In the initial part of the interview, students were asked to describe the ways in which they visualise a molecule, for example 2-butanol (see Table 8.2.). 2-butanol was selected because it is an example of a simple organic molecule, it is a substance the students had met during their laboratory experiments, it is a chemical compound introduced at high school (Barns-Graham, 1998) and it is a compound that is suitable for exploring different types of isomerism (structural isomerism and stereoisomerism).

Step 2 – Responses to the macroscopic sample of the substance

Then students were shown a bottle filled with a colourless liquid and labelled 2-butanol. They were asked to relate the ways in which they described 2-butanol molecule (their different representations – words, drawings and model/s) to the colourless liquid in the bottle.

Step 3 – Responses to supplementary sheets

To reveal students' visualisation of molecules as much as possible, after the initially described visualisation, the supplementary sheets with different representations of 2-butanol and SO₂ molecules were used as additional stimuli.

Another intention was to find the link between the ways students visualise molecules

and their understanding of each isomer type addressed by the tutorial in Study Two. For some isomer types (structural isomers and partially for conformational isomers) the insights were collected as a part of exploration of the student visualisation. For other isomer types, later on during the interview, a set of sheets, showing different structural representations of the selected molecules, was introduced and the students were asked to describe the structure/s. These sheets were introduced to a student after he/she had described their way of visualising molecules and after he/she responded to a sight of 2-butanol as a colourless liquid (all supplementary sheets are included with the interview transcript in Appendix 5).

The phenomenographic interviews were exploratory and open-ended. It has been suggested that such interviews provide a greater breadth than other types of interviewing, for example structured interviewing (Fontana & Frey, 1994). The first question was common to all interviews and established the frame of the researcher's interest. The initial intention was to get students to relate different representations of the same molecule. In their description, other features of molecules such as bond vibration, bond angle and intermolecular forces were sometimes discussed. The essential chemical terms, associated with the features of a molecule necessary for understanding stereochemical phenomena (an atom, a bond, shape of molecule etc.) were selected from the course materials for exploration. When students mentioned these terms in the interview, their understanding was explored. The path of the interview was open and not predetermined.

The interviews were audio-tape recorded and lasted approximately 45 minutes. Components of the interview are shown in Table 8.2.

(b) Students' Drawings

As chemistry is explained not only in the form of words, it was expected that the students could employ different ways in expressing the ways of experiencing chemistry. Gabel (1999) described that chemistry is mostly presented and instructed in a symbolic way using drawings, therefore, it is to be expected that the students will respond to chemistry phenomena in a similar way. For that reason, students were supplied with blank sheets of paper and had an opportunity to draw or write on them, if and when needed.

Table 8.2. Components of the interview employed in the study.

Components of the interview/questions	The aim:
<i>Start of interview (Research Question 3a):</i> How would you describe, to a person who knows nothing about chemistry, the way you visualise a molecule, for example 2-butanol?	To find out ways in which students visualise molecules and the nature of their understanding (symbolic, microscopic, macroscopic).
<i>Open-ended questions including:</i> Could you draw/describe what you are saying/drawing ... What do you mean by ... How would you describe an atom/a bond/double bond/a shape of ... What might be/is happening here?	To find out the depth of understanding across the threefold nature of chemistry and about links between ways of visualising molecules and the understanding of stereochemistry.
<i>A bottle with 'real' liquid labelled 2-butanol shown (Research Question 3b):</i> How would you relate your description and/or drawings of 2-butanol to the content of this bottle?	To find out how students relate their visualisation to the macroscopic sample of the substance.
<i>Supplementary sheets introduced (Research Questions 3a and 3 c)</i> How would you describe these structures here? How do they relate to each other?	To check/confirm student visualisation initially described and to find out students' awareness of different isomer types.
<i>End of interview:</i> How do you go about learning of stereochemistry? How do you know that you have learnt something?	To combine with student visualisation in assigning student approaches to learning.

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Apart from being able to verbally describe their ideas, the opportunity to express their conceptions in a form of drawings provided the participants with an additional perspective. During the interviews, there were participants who provided the researcher with both rich descriptions and many drawings; there were participants who more readily talked than drew; and there were those who were weak in verbal description, but provided highly informative drawings.

(c) *Supplementary Sheets*

As indicated earlier, researcher-generated supplementary sheets with different structural representations were made in advance and used during the interview process (see Appendix 5).

It was aimed that the student responses to the representations of 2-butanol on the sheets could be compared to the description of the ways the student visualises molecules given in the first part of the interview and that any agreement or disagreement between the two can be made in the data analysis process (multiple data source increase validity).

Also, it was hoped that the responses to the structures of various compounds on the sheets would contribute to the analysis of students' conceptualisation of different isomer types.

(d) Other Instruments

Student chemistry background before entering university or student course/exam results were also used as other data to indicate the profile of participants who took part in the study. In addition, the researcher's field notes, that were written on the sheets during or immediately after the interview, were used as an additional data source.

8.2.3. Analysis of Data in Study Three

All students were coded by pseudonyms. All 25 interviews were transcribed verbatim. All transcripts except one were done using a word processor. Transcription of the interviews mainly followed the conventions suggested by French (1989). Researcher generated documents (students' diagrams and supplementary sheets), and researcher's field notes were attached to individual transcripts and considered during analysis

The use of MS Word enabled the researcher to sort the students' quotes more easily for use in further analysis.

A phenomenographic approach was used to analyse the data in this study. The research questions initiated the three phenomena to be analysed, each related to one of the research questions. Table 8.3. shows the summary of the phenomena under the interest of this study that were named according to the research questions.

Table 8.3. The summary of the phenomena under investigation related to the research questions.

Research Question	Phenomenon (focus of analysis)	Investigation
3 a) How do students approach visualisation of molecules?	(i) Visualisation of molecules	Of students' concepts or the ways of experiencing (describing) the visualisation of molecules
3 b) How do students relate their visualisation of molecules to a macroscopic sample of the substance?	(ii) Visualisation - Macroscopic sample of the substance relationship	Ways of experiencing (describing) the macroscopic nature of the substance (2-butanol) in relation to their visualisation
3 c) In what ways do students conceptualise each isomer type?	(iii) Conceptualisation of each isomer type	Ways of experiencing (describing) each isomer type

Pavlinic, 1999

For each phenomenon, the detailed analysis, results and discussion of the results are given in the separate sections:

8.3. – Visualisation of Molecules

8.4. – Visualisation versus Macroscopic Sample of the Substance

8.5. – Conceptualisation of Different Isomer Types

8.3. VISUALISATION OF MOLECULES

8.3.1. Analysis of the Ways Students Visualise Molecules

The phenomenographical analysis that was employed in the analysis of this phenomenon is described below.

Phase One

Step 1 – Initial visualisation

All interview transcripts were read as a whole repeatedly. All documents (student drawings, supplementary sheets with researcher's field notes written during and immediately after the interview) were assigned to adequate utterances. The analysis started with individual sets of data. Each included the interview transcript, the student's drawings and the supplementary sheets with the researcher's field notes. In the first step, the analysis of student visualisation considered the student initial description (visualisation in mind), student drawings and the description the student gave as the interview went on.

Table 8.4. shows the summary of step 1 for the selected participants. The complete table for all participants involved in the study is available in Appendix 5, (c) Analysis process, Step 1.

Table 8.4. The initial step of the analysis of individual data.

Participant pseudonym / transcript no.	Visualisation		
	Initial /start of the interview		Developed as the interview progressed
	In mind	Drawing	
Paul (2)	name -> structure -> SF, constant movement, awareness of atom sizes	linear B&S, 3D structural	skeletal, SF model
Ben (3)	description of linear structure	linear structural formula	3D structural, B&S
Andy (7)	3D molecule, liquid	3D structure with detailed explanation	from notion of liquid to 3D structure
Jack (24)	describes his B&S drawing	incomplete, fragmented drawings, none correct	aware of SF picture of electron clouds, of bent shape of a molecule
Mark (25)	detailed description of 3D structure	3D z-z structure	none is true representation
Rudy (1)	z-z wormy looking thing, colours	SF model, skeletal, liner cond. and empir.	different ways, integrated
Tammy (4)	description of skeletal structure	skeletal, B&S to z-z shaped structure	z-z structure
Cara (12)	cloud of e ⁻ around nucleus, OH, covalent bonding, polar, linear 2D structure	linear, valence e ⁻ in it	unfamiliar, but built B&S model, computer images
Meg (22)	attempt to describe linear structural formula	incorrect partial linear drawings	word -> split the word endings (fragments from lectures mixed up)

SF – space filling model

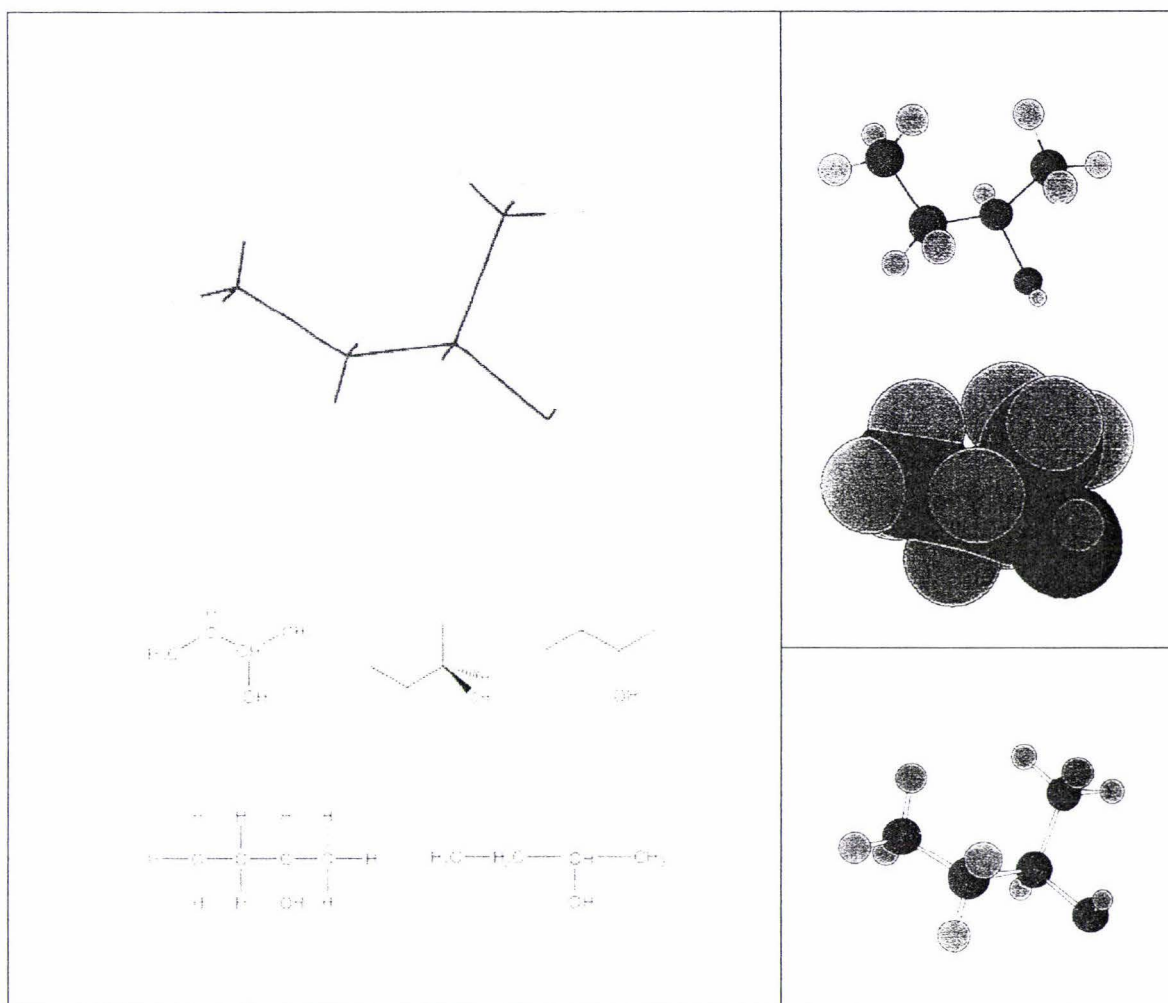
B&S – ball and stick model

z-z – zig-zag structure

Step 2 – Responses to supplementary sheets – Contribution to visualisation

Later, the other student responses from the interview were considered. Those included student responses to the researcher generated supplementary sheets (see Figure 8.1.), student responses to physical ball and stick models they had made during the interview and student responses to a colourless liquid in a bottle shown to the students during the interviews.

The sheet showing different representations of 2-butanol molecule was shown to a student and the student was asked to comment on different representations, to select those preferred and to describe why the selected representations were preferred.



Pasimic, 1999

Figure 8.1. The supplementary sheets with different representations of 2-butanol that were shown to the students to collect additional responses at the end of the interviewing process.

The results are given in Table 8.5. Only data related to the participants selected in Table 8.4. are included. The complete table is given in Appendix 5, (c) Analysis process, Step 2.

Table 8.5. The additional data that were considered in the analysis of student visualisation.

Participant pseudonym / transcript no.	Responses				
	Symbolic		Microscopic		Observable
	Linear	Shape showing	Computer images	Physical b&s model	
Paul (2)		**Lewis	**SF	*	micro, g-l state comparison
Ben (3)		**Lewis/ z-z cond.	#*		lab classes
Andy (7)		**Lewis	*B&S, #*SF	*	interaction between molecules in liquid, moving of particles
Jack (24)			**SF	# (model with no Hs, no additional sticks)	H-bonding, misconception of
Mark (25)		**Lewis	**SF	**	micro-symbolic, movement, intermolecular forces, g-l-s comparison
-----	----	-----	-----	-----	-----
Rudy (1)		**Lewis/ skeletal	**SF	*	word 2-butanol floating around, not molecules, in acid is H ⁺ ion
Tammy (4)		**Lewis/ skeletal	*B&S	*	(l), no micro link, like water, without label wouldn't have a clue
Cara (12)	**struc tural	*Lewis	*B&S/ *SF	#*	hard to connect with micro-symbolic, awake, very visible, thousands of them moving around
Meg (22)		*#Lewis	#*SF	##	one mole of these diagrams, mole of particles, depends on conc.

Pavlinec, 1999

** very familiar, preferred, detailed description and confidence

* familiar, find them useful

#* familiar when reminded

#* unfamiliar but getting used to them

unfamiliar, not used

Step 3 - Consistency between initial visualisation and the responses to supplementary sheets

Once the results of both Table 8.4. and Table 8.5. were combined it was possible to look for an agreement (consistency) between the initial way the student described his/her own visualisation, his/her drawings (initial visualisation) and his/her responses to supplementary sheets that were implemented in the later stage of the interviewing process. If the description/elaboration of the representations selected from the supplementary sheets matched student in-mind visualisation given earlier in the first

part of the interview (e.g. linear structural formulae was selected and described as familiar from high school, easy to use etc. and the same structure was described and given in a form of drawing when describing visualisation) the consistency was assigned. Because many representations were given in supplementary sheets and a student commented on all of them and because student visualisation also involved multiple representations of a molecule, in some cases partial agreement was found (e.g. agreement when the physical ball and stick models and the microscopic computer images were discussed, but disagreement in structural representations described in visualisation and selected from the supplementary sheet as a preferred one). If the responses to supplementary sheets did not match the in-mind visualisation given earlier, no consistency was assigned. Table 8.6. shows the results for the same participants that were selected in Tables 8.4. and 8.5. respectively. The complete table is given in Appendix 5, (c) Analysis process, Step 3.

Table 8.6. The consistency between the initial student visualisation and student responses to the supplementary sheets for the selected participants (when Table 8.4. and Table 8.5. were combined).

Participant pseudonym/ transcript no.	Initial visualisation	Responses to sheets	Consistency
Paul (2)	2D -> SF	2D -> SF	*
Ben (3)	2D	2D shape showing	*
Andy (7)	3D, wedges	2D shape showing	*
Jack (24)	2D or 3D B&S attempt, all incomplete	B&S	*
Mark (25)	3D sophist.	B&S, SF, 2D shape	*
-----	-----	-----	---
Rudy (1)	3D sophist.	2D shape	*
Tammy (4)	2D shaped	2D shaped	*
Cara (12)	2D	2D	*
Meg (22)	2D lin, incomplete	B&S	#

* consistency between initial description and responses to sheet diagrams
*# partial consistency
#* initial description and shown diagram responses are mostly inconsistent
no consistency, responses to sheet diagrams differ from initial description

Pavlinic, 1999

Phase Two

Step 4 – Meanings emerged from quotes/drawings

In the second phase, attention was shifted from the data which included individual students’ quotes and associate drawings to the meanings embedded in the quotes or

shown by the drawings, regardless of whether these different meanings originated from the same individuals or not. The quotes from different participants with different meanings formed a pile or 'pool of meanings'. Similar meanings were identified in the sets of data (quotes, diagrams) derived from different participants.

Although all transcripts except one were electronically available, the criteria for the selection and inclusion of the quotes and diagrams in the thesis to illustrate different meanings depended on the electronic availability of the students' drawings (this did not affect the analysis, but only reporting). For that reason, the quotes and drawings were selected from the participants of which:

- either the student drawings were available in an electronic form (diagrams were scanned and included to support an interview given in the Appendix 5);
- or the diagrams were made from the students' drawings earlier (for the purposes of a seminar or a conference paper) and were also available in an electronic form.

Criteria used involved five aspects:

- does student visualisation of molecules agree with the representations/models accepted by scientific community and being introduced at school/university;
- is student visualisation constituted of mono- or multi- structured components (narrow or extensive visualisation with many ways/representations/models);
- does student visualisation show the relationship between the components of visualisation;
- how comprehensive explanation of a phenomenon was given in a description;
- is visualisation experienced (described) as predetermined or infinite process.

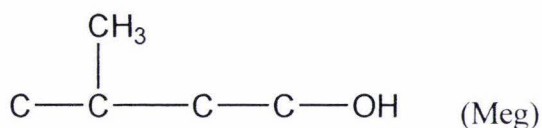
In this step, initially three different meanings were differentiated. The selected quotes and supported diagrams given below illustrate the different meanings and the visualisation associated to each meaning.

The first meaning, named *Unsatisfactory visualisation*, included participants' quotes and supported diagrams that indicated poor visualisation:

Meg/Transcript no. 24:

I visualise it as a skeletal formula of CH three and the way it has been drawn in the text books, CH three coming down, the stick and the stick by them and ...

um, in my mind I am thinking, .. um .. I have to see the word first and then I think of the ending of the alcohol group OH and then I think of butanol which is four carbons and two is the side chain, um .. I think if I haven't seen the structures, if I only have been taught since January the way I should look, I can't visualise it completely in my mind, I can't break them up (Meg)

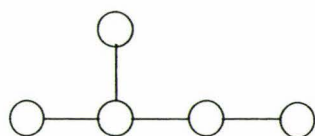


Jack/Transcript no. 22:

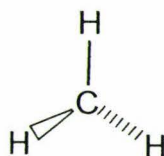
The way I visualise it...Well to someone who had no knowledge I suppose I'd have to describe...I guess I'd have to use the ball and stick model to try and describe it. I'd probably draw a diagram. Umm

Well, what's butanol again .. I'm absolutely horrible with prefixes .. Butanol's five isn't it? Wait, I did something wrong. OKAY so two butanol. .. Um, I guess to start off I might just draw something like this. And what have we got? Two butanol so something like that. And I might go on to more detail later and add the hydrogen atoms onto it, .. um .. you know, ... I suppose I would describe, I'd start with the ball and stick model [(i)] ...

...that's incredibly simple well, for instance, to represent a ball .. they are simple CH₃, .. so ... I mean this one [(ii)] shows ... a better idea of how it actually is in reality and .. Of course that is the next step, I mean drawing .. using that and that, you know, .. to show the .. um .. bonds, you know, whether it's behind or on the front, you know, .. actually where it is. That would be another step up, you know, ... So, going on from there [(i)], so it's building on levels, ... showing more and more each time. But, I can remember my teacher with first chemistry course I have had, he's started with the really simplistic models balls and sticks and we'd done it from there ...(Jack)



(i)



(ii)

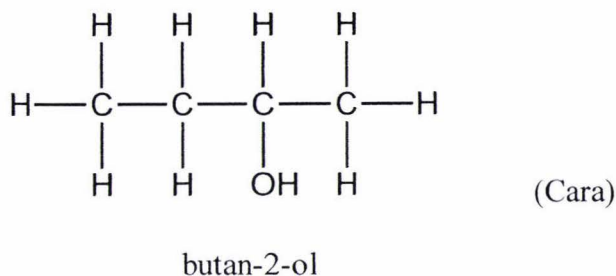
(Jack)

The other meaning included participants' quotes and supported diagrams that indicated *Satisfactory visualisation*:

Cara/Transcript no. 12

... four carbons and butanol, and butanol, 'cause it's an alcohol has an OH group, so that would be like an OH group coming off the second carbon or

whatever, so, yeah, I am not really sure I forgot .. to tell about covalent bonding and stuff and how the OH group would be slightly polar cause of the charges on the atoms, yeah I guess (Cara)



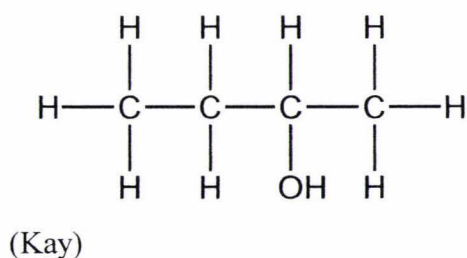
Kay /Transcript no 21

It's four carbons in a chain, on the second carbon it's got an OH branch cause it's an alcohol, it's got hydrogens around each of the carbons cause all of them are single bonds [drawing labelled (i)]

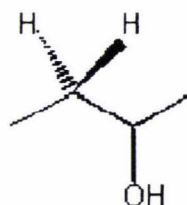
.. Yeah, mainly .. [visualise like (i)] 'cause last year we did all our drawings like this [like (i)], so I was still sort of like here, I know which one is at the moment, they encourage the three dimensional thing [drawing labelled (ii)]

They are both the same molecule, they both are structural .. this seems more accurate [(ii)] ... it shows the actual shape of the molecule, that one is just drawn, simple version ..

Because the carbons are diagonal on the chain .. [(i)], I don't know what to say .. really I am not good in explaining things, 'cause the actual shape of molecule is like that [(ii)], so it [the structure (i)] doesn't have the three-dimensional ... things, it's a planar.. This one [(ii)] tells you about the shape of the molecule.. (Kay)



(i)



(ii)

The next meaning, called *Developed visualisation*, included participants' very rich description supported by a range of diverse ways for representing molecules and indicated a very good visualisation. The use of student's own terminology (everyday language) was not treated as a waning factor in assigning categories:

Rudy/Transcript no. 1

I'm not 100% sure how I do that but I just know that 2-butanol is just a zig-zaggy wormy looking thing with the different, I actually had them in different colours, cause we used colours, we always use colours in chemistry with the red OH out the side of the second carbon ..

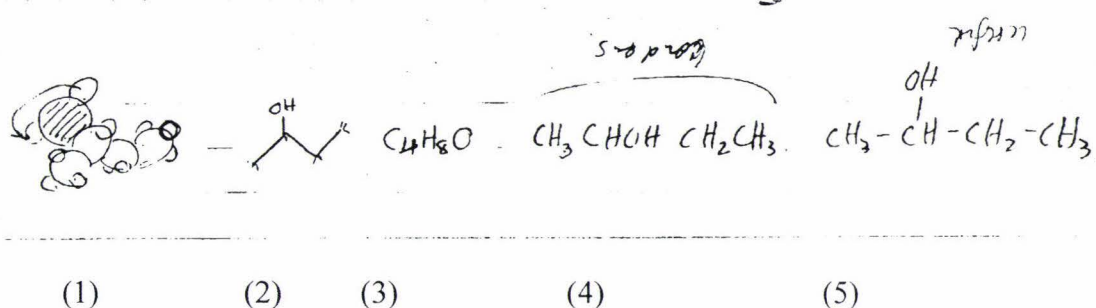
Yeah they are all squeeze, fluffy things that Tony [lecturer used space filling models] writes and everything [see drawing (1)]

That's how I am now writing, as it's quicker. [see drawing (2)]

Um 2-butanol, I better count all these things up I suppose. I have probably got the H and the O's around the wrong way, but .. [see drawing (3)]

Then you can do the condensed structure .. [see drawing (4)]

I can do the first bit before doing this one here . [see drawing (5)]



Um, I never been a fan of those [ball and stick models], but yeah, I am familiar with these guys. ... We used to use them at high school so I have no problems with using them. We used to have the other ones, the spaced filling ones, so that is like real easy for me to picture them, the space filling guys. It is just time consuming. You can picture it in your head anyway [laugh]. (Rudy)

Mark/Transcript no. 25:

Mark: 2-butanol. It's a chain of carbon atoms in a sort of zig-zaggy form, and it's got an OH group on the second carbon, um, .. [see his drawings]

OK, these solid triangles are representing the bonds with Hs, the bond's face is out of page and the dash lines are representing the bonds that go into the page and the single bonds are flat [see (i)].

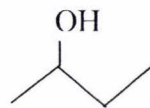
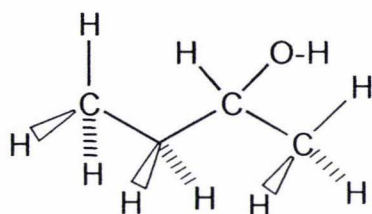
This is a structural representation attempting to show of the position of the atoms in 3D space but it's not really very accurate.

R: Why are you saying that it is not very accurate?

Mark: Well, with these atoms like that there are angle, the oxygen will affect the angles of other bonds and so you wont be able to draw exactly right.

[now he talks about other representations] There is the skeletal one [(ii)], which is just the minimum things, you don't have carbons and hydrogens drawn all here, you also have the sort of square one, .. has sort of straight chain and straight lines which really, doesn't accurate at all because carbons don't bond in a straight line, they bond in a zig-zag type of pattern ..

None of them really represents the real 2-butanol molecule.. um, that's probably because, some of, .. the skeletal one doesn't show very much at all, the straight chain one isn't accurate either, just sort of look as they all go into the pattern to stuck together, the one, that one with the dashed lines, I mean, .. it tries, but it's just not quite good enough to show you how it looks. The Chem3D program does a very good job there, and the use of models is good.



(Mark)

(i)

(ii)

Step 5 – Borderline cases

In this step, a differentiation between the ways in which students visualise molecules within the meanings took place. The process involved identifying similarities and differences and rearranging and narrowing the students' quotes, aimed at defining the core meanings and in examining borderline cases. The criteria for each group were made explicit (listed earlier in step 4).

For example within the meaning that was initially assigned to be unsatisfactory visualisation the differentiation was made whether the participants tried to employ one (Meg) or more different representations being taught at the lecture (Jack) in describing their visualisation.

Similarly, within the meaning that was initially assigned to be satisfactory visualisation, the differentiation was made whether or not a participant's visualisation was based upon only one way, either 2D or 3D, (Cara) or more ways in describing ways they visualise molecules (Kay).

Finally, within the meaning that was initially assigned to developed visualisation, the differentiation was made not only whether or not a participant's visualisation was based upon the integration of different ways of describing molecules (Rudy), but also on the process of how they perceive that integration (Mark).

Step 6 – Categories of description

The previous step of the analysis gradually led towards identifying different categories of description.

Once the different categories of description were formed, they were analysed in relation to each other and placed at specific levels in a logically structured hierarchy (Bowden, 1994; Marton, 1981; Marton & Booth, 1997; Marton & Säljö, 1984; Walsh, 1994). Value judgements of the researcher were entailed in the recognition of significant aspects of a phenomenon, but these were supported by argument as, for example, where a higher category was associated with a more comprehensive explanation of a phenomenon (see criteria listed in step 4 of the analysis). The increase in the students' ability to visualise molecules was shown as alphabetically ordered categories of description, the lowest starting with A.

The identified conceptions were analysed in terms of the referential aspects of the students' ability to describe their visualisation. Students' conceptions (descriptions and diagrams) were compared to the representations they had been taught, which represent the scientifically accepted representations of molecules used by teachers or textbook writers. The representations used to introduce the concepts in organic chemistry at Massey University include for instance, a variety of symbolic ways such as the use of structural formulae (linear or zig-zag), skeletal structures (formulae), and 3D structural formulae with the three-dimensional nature of the two-dimensional (2D) structural representation. Furthermore, the wide spread use of physical ball and stick models or space filling models for three-dimensional (3D) representation, or computer generated models are also representations used by teachers when introducing chemical concepts. The students who participated in this study had been exposed to all of these different representations.

The analysis of the ways in which students visualise molecules was not based upon which representation the students used, but on their ability to visualise one or more representations used in chemistry instruction and by professional chemists. The emphasis was given to the description of the similarities and differences between the categories. The outcome of the analysis derived in hierarchy of the categories.

All assignments of categories were checked by a researcher with experience in phenomenographic analysis (one of supervisors).

Step 7 – Approaches to learning

Student visualisation was seen as a dimension of student approaches to learning stereochemistry and was related to the main Research Question 3. In addition, at the end

of each interview students were asked “How do you go about learning of stereochemistry?” and “How do you know that you have learnt something?” The students’ responses were analysed according to the approaches to learning – deep, surface and achieving (strategic) (Biggs, 1999; Booth, 1997; Entwistle, 1997; Marton et al., 1997).

Step 8 - Additional analysis

Categories of description refer to the collective conceptualisation. As described, the quotes from different students contributed to each category. Furthermore, the data from one participant contributed to more than one category. However, the teachers are often interested in how many students from the class can be expected to conceptualise a phenomenon in each category. This additional step of analysis aimed to address this interest of teachers.

Once the categories were made, the quotes, drawings and other responses that were taken from the individual sets of data and assigned to categories (one or more) were allocated back to the individuals. That enabled the researcher to assign the categories (one or more) to the individual student.

If the individual data were allocated to more than one category, only one category to which most data were allocated was accounted for this analysis.

This additional step of the analysis can be supported by the generative research methodology, often present in educational research.

8.3.2. Visualisation of Molecules - Results

In this study, the ways of describing or experiencing visualisation are called ways of visualising or student visualisation. The initial findings represented the description (verbal and in a form of drawings) of what the students reported having in their minds when asked the question: “How would you describe, to a person who knows nothing about chemistry, the way you visualise a molecule, for example, of 2-butanol?” These findings were compared to students’ responses to the supplementary sheets, their responses to the physical ball and stick model and responses to a liquid in a bottle. Therefore, the student’s responses explored in different ways during the interview were considered and contributed to the individual sets of data.

Consistency in individual student’s responses is given in Table 8.7. The criteria

employed were illustrated in Phase One, Step 3 of the analysis process (section 8.3.1.). The results in Table 8.7. are based on the analysis demonstrated by Table 8.4. and Table 8.5 and summarised in Table 8.6.

Table 8.7. The consistency between the participants' initial visualisation and the responses collected later during the interviewing process.

Consistency	Participants	
	No. / of 25	%
Good consistency	16	64
Partial consistency	1	4
Mostly inconsistent	4	16
No consistency	4	16

Patricia, 1999

The results indicate good agreement between the ways the students initially described their in-mind visualisation (supported by their own drawings) with the other responses demonstrated later during the interviewing process.

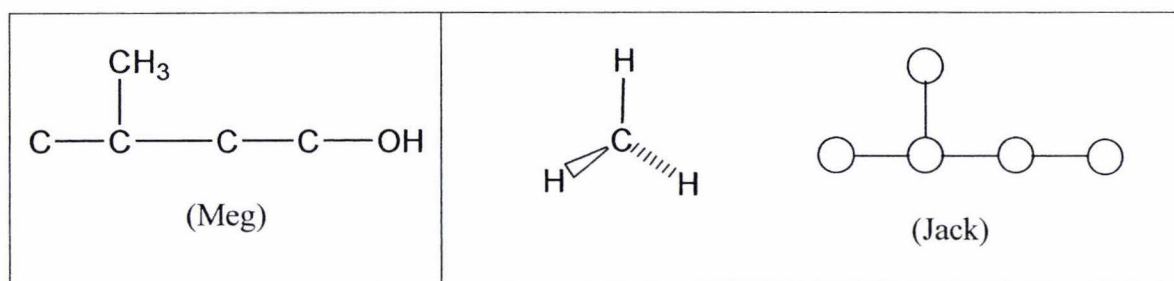
(i) Categories of Description

The quotes from the interview transcripts supported by the diagrams were classified into the categories of the ways in which students described how they visualise molecules. The ways in which students visualise molecules ranged from *Incomplete visualisations*, based on the fragments of symbolic representations only (the lowest category A1), to *Developed visualisation* (category E), in which the integration of the symbolic and microscopic nature of chemistry (including one student being aware of the macroscopic nature as well) was shown.

Five hierarchically ordered categories of description are given in Table 8.8.

Category A - *Incomplete visualisation*. Unclear and partial visualisation has been identified in this lowest, category A. It was found that the students attempted to apply one or more representations, but none were applied in a complete form. The students seemed confused by the number of different representations being introduced in the chemistry course. They were not confident in what they had described and were not able to identify or know how to apply any representations used in instruction. They made diagrams, but these mostly seemed as fragments of 'something' they have been

taught:



Two distinctive subcategories emerged:

A1 - in which student visualisation and description were based upon an attempt to recall pieces of a linear two-dimensional structure of the organic molecule, introduced at the lectures or seen in their textbooks. The students were not able to remember what that exactly was; the representations drawn were incomplete and poorly understood. The visualisation did not correctly match any form of the representations that was used in chemistry instruction.

A2 - in which student visualisation and description were based on attempts to recall some of the two-dimensional structures, and also the three-dimensional representations (ball and stick models) but none completely matched any of the formal representations used in instruction. The representations drawn, the models built and supported descriptions were incomplete, with a lot of mixed fragments of something they had been taught. Poor understanding was assigned.

In describing visualisation in subcategory A1, the students' descriptions and drawings seemed good enough, right and correct for them. These students were not aware of the wrong or incomplete application of one or more representations they had used. It did not seem wrong or incomplete to them. Student visualisation could not be attributed to any particular representation/model, nor did it interpret the correct chemical composition (see Meg's quote given earlier in 8.3.1. Analysis, Step 4)

In subcategory A2, an attempt to employ different representations/models was present in describing visualisation. However, an assumption such as that used by Jack that the ball is a substitution for a CH_3 group was incorrect and did not match any representation or model given in the formal chemistry instruction (see Jack's quote in 8.3.1., Analysis, Step 4). In this subcategory, the students were more aware that their visualisations were incomplete, and that the representations they used did not interpret the correct chemical composition:

I suppose I still visualise it as the ball and stick model, you know, ... I actually, used to not really thinking about the hydrogens, just adding the models after thought, I guess, I've got into the habit of thinking of just .. the carbons there, you know, forgiving about the hydrogens due they splayed off, which is a bad habit I guess. Um, when I think about three-dimensional structures in my head, ... I mean, I am not thinking of the actual shape, I mean, that's one of the, the good thing about that representation is it's time saving, the bad thing is it's very poor representation of how it's actually is in three dimension. (Jack)

Table 8.8. Hierarchical order of categories of description showing student approaches to visualisation/representation of molecular structure.

Category / Referential aspect	Structural aspect (Focus)
A - <i>Incomplete visualisation</i>	No one representation clearly understood or preferred.
A1 – <i>2D based incomplete visualisation</i>	Visualisation based on an attempt to apply only 2D representations (fragments of the 2D structural representation). Focus not clear, inappropriate, very poor understanding.
A2 – <i>2D and 3D based incomplete visualisation</i>	Visualisation based on an attempt to apply several representations (fragments of one or more 2D and 3D representations/models), all poorly understood and applied. Focus not clear.
B – <i>One-representation based visualisation</i>	Visualisation based on one representation/model. Focus on the one representation/model introduced to them, which is preferred, well understood and used regardless of the aspect being investigated.
C – <i>Multiple representations – disintegrated visualisation</i>	Visualisation based on the use of different representations, not integrated together. Different representations/models for different purposes.
D – <i>Multiple representations – integrated visualisation</i>	The visualisation (whole) integrates different representations/models. Focus on integration of different ways.
E – <i>Developed visualisation</i>	Visualisation integrates multiple representations, all clearly understood, detailed description. Focus on the process open to different 2D and 3D representations, all aimed to discern different aspects of the phenomenon and all contribute to the wholeness (visualisation). Visualisation is seen as on-going developing process, open for new possible ways/representations/models (aspects) to be added.

Pavlinic, 1999

Category B - One-representation based visualisation. Student visualisation was based upon the description of one preferred way of representing molecules. Although these students were aware of the other representations they had been taught, they always shifted back to the way they preferred, regardless of the concept being investigated. The students seemed convinced that using the preferred visualisation will in all probability result in a successful outcome in an unknown situation such as a test or exam. The preferred visualisation could be based on a well-understood two-dimensional or three-dimensional representation.

A preference to employ one representation was an approach that worked perfectly well for certain aspects of chemistry phenomenon, for example the use of the ball and stick model when exploring the shape of molecules. However, it appeared inadequate when exploring other aspects such as assigning the polarity of a molecule and investigating intermolecular forces.

For example, Jody described how she used the ball and stick modelling kit to help her understanding of lectures “.. and again I’ll sit and play with my ball and stick models at home, kind of, to get an idea what we are talking about ..”. Later on while responded to the supplementary sheet showing the structural representations of enantiomers, she explained:

Um, that’s an enantiomer and it’s not superimposable I think, you see again I kind of meant to try go back to the ball and stick to see if I can place that on top of that, which I can’t, so it’s a mirror image, it’s not superimposable ..

The shift from one model to the preferred model was confirmed over and over again during the interview. Responding to the sheet showing different representations of SO₂ molecule later during the interview, Jody explained:

I look at that one straight away to give me an idea what we are talking about which is a linear, .. um, but I would probably choose this here, the ball and stick with the double bond, I would say would be a representation with shape ..

While exploring the ball and stick model is useful in understanding shape and exploring enantiomers (nonsuperimposable isomers), for exploring other aspects of chemistry the preferred ball and stick model may be limited and the use of structural representations may be more useful.

Talking about teaching and learning of stereochemistry Jody explained:

I don’t know if there is an easy [teaching], there is no an easy way to represent

it. I think it's a bit unfortunately it's about six different ways to represent everything, um, just learning one consistent method would be nice ..
I definitely need a sort of visual representation, I prefer, like, ball and stick model, makes a lot difference to the way I learn

Category C - Multiple representations – disintegrated visualisation. An appreciation of the different ways in which molecules could be represented was identified in category C. The student visualisation recognises more ways of seeing molecules and includes more than one way of representing molecules the students had been taught, either 2D or 3D. Different representations/ways of visualising are employed for different purposes, as necessary. The purposeful use of the one representation/model excludes the possibility of achieving the same purpose by the use of other representations.

An attempt to apply one representation was described for an isolated, separate purpose, while a second representation might be used when discerning another aspect of the phenomenon. However, these conceptions did not show that the students appreciated switching from one representation to another.

At the start of the interview, Erica described her visualisation of a molecule 2-butanol:

2-butanol, .. yeah .. well, I would say it had four carbons with an OH off the second carbon and then if you put in all the H's to make sure that the carbon had four bonds each.

R: Would you like to draw that you were saying?

Erica: [she draws linear structural formula] I would say that goes like that.

R: Does this structure show something you have in your mind, the way you imagine a molecule?

Erica: When I think of a molecule? Yeah.

Later on, she made a ball and stick model and described its use:

It's quite good, it sort of puts in, sort of, perspective it gives you a 3-D imagine, you can make up these little isomers because you can turn it around and have a look. (Erica)

Then she was asked to relate the model to her initial visualisation (the description and the drawn diagram given earlier):

Well the ball and stick, as I said before, is a 3-D and I think you can rotate it, where as this one here you cannot really rotate it. You have to rotate it in your mind. I think the ball and stick ... sort of, helps you rotate it and you can see all the different isomers that you can have .. just using the OH of the second carbon and that sort of thing. It is generally easier to see. (Erica)

The purposeful use of the ball and stick models in identifying isomers was experienced

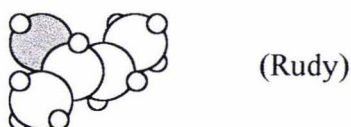
as disconnected from the ways she described visualisation of molecules.

Kay described how she visualises 2-butanol as a linear structure having “four carbons in a chain, on the second carbon it’s got an OH branch cause it’s an alcohol, it’s got hydrogens around each of the carbons cause all of them are single bonds” (i), but the other, shape showing skeletal structure (ii) or the ball and stick model was seen as different and to be used only to “show the actual shape of the molecule” (see the quotes and diagrams of Kay given earlier in 8.3.1. Analysis, Step 4).

Category D - Multiple representations – integrated visualisation. More than one way of visualising molecules also describes this category, but in this category the different ways of visualising are more integrated and students readily switch from one way to another. Both two-dimensional and three-dimensional ways of representing molecules were properly understood and combined into the more global way of visualising.

Although one way was preferred when analysing one aspect of molecules, quite often the insights of the other ways were recalled for supplementary understanding. In one example the understanding of skeletal formulae employed in one situation recalled the shape that was previously explored by the use of 3D ball and stick models.

A way of visualising described by Rudy (given earlier) is an example of visualisation in which different ways of visualising were integrated into the whole. The following diagram supported her initial description:



Later on, having drawn the skeletal structure as well Rudy explained: “.. if you have to look at them in, like more depth, like now that I have drawn this, I know that this here [in skeletal structure] is cause of that guy [pointed at the oxygen atom at the ball and stick model], ... you can see how the electrons repel each other away, the bonds and that stuff away”.

Romy’s concluding discussion at the end of the interview was a summary of her visualisation in which she sees the purposeful use of different representations; it also revealed her ability to switch from one representation to another depending on the aspect being studied:

I think the representation we have and about how you think about molecule, depends on what you learn about the molecule, like if you learning about its reactions, you like just draw like a skeletal structure, but if you are talking about um, its electrons or the shape of this molecule you might use some other structures, yeah, depends whether we are talking about the bonds, intermolecular or intramolecular um, bonds, like you know attractions and stuff as to whether use like a ball and stick or use more the .. like that one [space-filling model on the sheet]. Like if you are talking about intermolecular you might use that one [zig-zag condensed formula] (Romy)

Andy's response to the supplementary sheets showing the different representations of SO_2 was placed in this category:

I think that I would actually choose the Lewis diagram because, um, with the lone pairs saturated around it like that, is easy to see ... where bonding, like, takes place, also it is oxygen here and it's got a negative charge on it, so on the paper, that one is easier, that one is most informative but of course if I imagine in my mind this one here [ball and stick model], I think would be better. Um.. yeah, also through this one [compare the ball and stick with the space filling], especially with more complicated molecule with a tetrahedral carbon, um, it's far easier to see separated atoms on it, because they are not sitting too close to the carbon ...

I am most familiar with that [skeletal] and the reason is 'cause we are not drawing a molecule, that's the way I draw, it's just quickest, easiest, it doesn't show the actually three dimensional structure on it but if you know enough then you would be able to work out it by yourself ... (Andy)

The description given above shows that the student distinguished the visualisation in mind from the representations used in drawings and highlighted that one representation [skeletal structures] might be explainable enough if "you know enough".

The awareness from one representation/model present in the description of the other was found in Jody's description:

Um, if you start with, .. how do you call this, structural formula, ... the written version there is drawn out exactly in the same format of that CH_3CH_2 .. That's .. skeletal formula .. which is more related to this [ball & stick model] because it gives you the shape of the molecule more, um without filling all of hydrogens which are, .. I guess, assumed to be obvious .. this .. makes four bonds around each carbon

R: How do you mean to be obvious?

Jody: Because, .. [laughs] 'cause you have been taught that if you are drawing the skeletal formula there is going to be each carbon, four bonds around it. Therefore, you don't need to draw on hydrogens .. Oh, it shows the zig-zag form, that shape because of the way that the atoms want to orient themselves to get maximum distance apart, well, it has been obviously what this structure is

..

Category E - *Developed visualisation.* The visualisation in this highest identified category contains all of the attributes that were described in category D; the understanding of all different 2D and 3D representations/models used in the description and the ability to switch between them depending on the aspect being analysed. Students in this category were able to give detailed descriptions and were aware that their visualisation is based upon the ways they have been taught. Visualisation is seen as a constant developing process that provides an opportunity for new ways of seeing or representing the phenomenon to those already known. All ways of visualising contribute to a more integrated visualisation, each addressing a different aspect of the phenomenon.

The purpose of the different ways in which a student visualised molecules was clearly understood, but “none are true representations” (Mark). The different representations were aimed at helping students understand different aspects of chemical reality. This is consistent with the definition of representation by Estes (Bodner & Domin, 1998) who claims that “a representation stands for but does not fully depict an item or event”. The visualisation described by Mark is a construct that agrees with the nature of constructivism as described von Glasersfeld (1995):

From the beginning of the 5th century B.C., sceptics have shown that it is logically impossible to establish the “truth” of any particular piece of knowledge. The necessary comparison of the piece of knowledge with the “reality” it is supposed to represent cannot be made, because the only rational access to that reality is through yet another act of knowing.

(The concept of knowledge, para. 1)

None of the representations/models employed showed the nature of the molecule with all the characteristics that the student was aware of. A switch between the microscopic and symbolic nature and different representations was used when appropriate. All representations/models were integrated to form a whole picture with properties, interpreted for instance through bond rotation, intermolecular forces, electronegativity or 3D shape of molecule. Andy stated “1-butanol is a liquid” [initially he talked about 1-butanol instead of 2-butanol] before being confronted with a colourless liquid in a bottle labelled 2-butanol:

I’ll first of all start with telling them that it’s three dimensional molecule ... to someone who doesn’t know very much chemistry, um, sort of, I would so say that it’s a series of carbon atoms bonded together and each carbon atom has one or more hydrogens bonded, oh 1-butanol, [he was asked about 2-butanol]

so each carbon atom would have two hydrogens bonded to it except the end bonds and at the end of the chain would be an alcohol group which consists of an oxygen and a hydrogen atom, joined to the carbon atom. I think the most important thing to understand that it's three dimensional molecule, it's not just a flat, if you draw it on the paper would be something that occupies a volume.

Three-dimensional 1-butanol [draws zig-zag structure with solid triangles and dashed lines on around each carbon]. That's probably the best way I draw it the way it's shown, like this in a, you have, just to explain to the person that drawing what these things here mean, so they can get into a ...

.. Um, .. probably would be a picture more as, as one, more as one kind of around particle and butanol, 1-butanol being as a liquid. 1-butanol is a liquid ha? 1-butanol is a liquid. So, I would probably just picture it as a little liquid particle, like around in solution all with the other particles...

Later on, visualisation of this participant involved a discussion of intermolecular attractions. These notions remained when moving from the atomistic level (visualisation of an atom or a bond) to the holistic (visualisation of a molecule). The visualisation was described as a developing process, with awareness that the advantages and disadvantages of any particular representation contributed to the vision of the molecules.

The categories as described are hierarchically ordered and show an increase in the sophistication of the ways in which students visualise molecules.

(ii) Student Approaches to Learning of Stereochemistry

The students' discourse and particularly the ways they described visualisation, because of the three-dimensional aspect involved, was seen as a dimension of their approaches to learning of stereochemistry. Entwistle (1997, p. 91) also described how visualisation was often part of a student approach. According to Entwistle (1997) when students talked about their revision strategies, they "also brought to light the widespread use of mnemonics and a reliance on visualising the structure of notes, sometimes in the form of mind maps. Description of these revisions often stressed visualisation, and the way the image helped to trigger memory" (p. 87). Visualisation was often described as a part of the process in bringing an understanding to mind (Entwistle, 1997, p. 91). It was seen as a part of activity of bringing together what were initially loosely related ideas and experiences in the creation of 'knowledge objects'. Defining features of 'knowledge objects' involves awareness of a tightly integrated body of knowledge, visualisation and 'quasi-sensory' experiences (in which the summary notes were assessed visually),

awareness of the unfocussed aspects of their knowledge and use of controlling explanations. Visualisation helped the students to 'pull up' additional information and specific details which they had memorised separately. In this study, the ways of visualising molecules were seen as parts of students' approaches to learning in which the students attempted to bring together a range of related ideas in describing visualisation of molecules. A phenomenographic study by Davies Burns (1997), which explored student conceptions of atomic structure and bonding also related student visualisation to their conceptions and approaches. In addition, the students' responses to the questions "How do you go about learning of stereochemistry?" and "How do you know that you have learnt something?" were also analysed in relation to approaches to learning – deep - D, surface - S and achieving - A (Biggs, 1999; Booth, 1997; Entwistle, 1997; Marton et al., 1997).

In order to analyse how first-year undergraduates approach the learning of stereochemistry the following assumptions were comprised.

1. The characteristics of the approaches were based on the initial description for deep and surface approaches (Marton & Säljö, 1976). Due to the achieving approach that was added to the previously identified deep and surface approaches to learning, defining features of approaches to learning were taken from Entwistle (1995, Table 1. defining features of approaches to learning, p. 48).

Deep approach - Intends to understand learning material. Is actively interested in the course. Looks for patterns and underlying principles within learning material and relates ideas to previous knowledge. Examines argument and logic critically, and checks for evidence.

Surface approach - Intends to fulfil the immediate task. Worries about work. Studies with no clear strategy or purpose. Attempts to memorise facts within the learning material. Finds it difficult to make sense of new ideas. Does not search for patterns or connections across different parts of a course.

Achieving/Strategic approach - Intends to do well in assessments. Worries about finding the right study material. Focuses on assessment criteria, and shapes work to meet the lecturers' perceived needs. Studies consistently to maximise grades.

2. The deep and surface approaches are not personal traits or fixed learning styles. Students adopt an approach which is related to their perceptions of the task. At

different times the same students can adopt and do adopt different approaches in different subjects because they perceive that they make different demands upon them.

3. Memorisation can be a feature of both the surface and the deep approaches, but it plays a different role in each.
4. The deep approach and surface approach are manifestations of the intentions that the students possess (either to understand ideas for themselves or just to cope with course requirements)
5. Students typically were found to work through several revision stages in which different learning approaches were used (Entwistle, 1997).

Examples of students' responses given below illustrate approaches to learning showed by the participants of this study.

During the interview Meg repeated her learning approach several times:

Learning .. mainly from when I listen to a lecture I write down as much as I can .. and I have to speak to someone because often I can't have the whole picture ..

.. I am trying to remember what the picture is .. I am trying to remember, like, first of all, what are the functional groups, trying to remember molecular formula .. I just look at it and try to remember what it looks like and try to remember word associated to it and hopefully I can understand it in my own way .. (Meg)

Mag's discussion was assigned to a surface approach in which memorisation was used as a process of collection of discrete units of information (Marton & Säljö, 1976). On the other hand Ben, with a deep approach talked about understanding, applying, revision and seeing something in a different way:

Ben: Usually, if you understand it .. [talks about learning]

R: How do you know that you have understood it?

Ben: Well, it's like, if you go away and how you can, you know, do the question and get it right, which is, yeah, .. that happens and that's you understand ..

.. Yeah, I'll probably, if I'm studying and do revision of what you already know you would understand, and yeah, so, you just reread the notes and then you get ball and stick and that things, um, yeah.

.. Once you can do it on your own you obviously understand it, but if you don't understand it from the start, it is best to see somebody doing practical demonstration, to show you how you have to do it, and if you go away and can do it you understand it.

Quite often different strategies were involved in achieving understanding and contributed to a deep approach. Cara described:

.. I just try to imagine the bonds stacking of the angles and yeah, I found that much easier, if I just try to memorise, it doesn't work.
.. I usually look at them in the textbooks, and some of them are really good, one with little tables or summaries and, and I found it easier, but I have to work really .. read through and find out what I can control mentally, what I understand, so I can write so I understand it, yeah, so I come back so and memorise and understand it better.

This study revealed that in learning chemistry students combine different learning approaches. Many students talked about repetition. For example Thai described:

In chemistry it's like you have all this information, different um, mechanisms and formulae and everything and so you need actually to find out what is important in going about learning that. So, it's probably my best approach how I go, repetition, study, yeah. Repetition is looking at them from different aspects, is probably important as well, relating to other things, because I mean one thing relates to other thing, so if you follow, if you cover everything you are more likely to have covered the same thing more than once. So definitely repetition is important. (Thai)

Thai's description in which she talked about repetition as seeking connections to other knowledge (e.g. "looking for different aspects" and "relating to other things" in the quote above) is seen as repetition in addition to deep approach and achieving meaningful learning. But, Thai also described that "you learn what you need for an exam" which was assigned to achieving or strategic approach.

Another student talked about repetition as important in learning stereochemistry, but also talked of his own development (changing as a person):

R: How would you know that you have learnt something?

Dan: Um, because four years ago I didn't know anything about chemistry and now I know something, I suppose I have learnt something, .. you know, day to day you don't really know, you believe something until you really have to use it either in exam or in assignments or wherever you use chemistry, so you have to use what you have believed I suppose, it's pretty hard to know that you have learnt something.

It was anticipated that in everyday studying time constraints and competing pressures often prevent students from completing the process which leads to full understanding, even when the intension was deep (Entwistle, 1997).

Student visualisation can be seen as a dimension of student's approaches to learning (Davies Burns, 1997; Entwistle, 1997). Table 8.9. shows findings obtained for the

selected participants in which student approaches to learning were assessed from the students’ responses to the last two questions during the interviews and the students’ visualisation (given in a form of identified categories of description. (The full table is available in Appendix 5, (c) Analysis process, Step 3a.)

Table 8. 9. The identified approaches to learning for the selected participants.

Participant pseudonym / transcript no.	Allocation of quotes/Category	Approaches		
		D	S	A
Paul (2)	D, C		✓	✓
Ben (3)	C	✓		
Andy (7)	D, E	✓		
Jack (24)	A2		✓	
Mark (25)	E	✓		
-----	---	--	--	--
Rudy (1)	D	✓		✓
Tammy (4)	C		✓	
Cara (12)	B	✓		✓
Meg (22)	A1		✓	✓
Jody (20)	B, C, D	✓	✓	

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In most cases the participants who showed visualisation assigned to higher categories of description showed the characteristics of deep approach. Although the exploring of the student conceptions of learning was not the aim of this study, it can be found that the student description by chance cover some of the conceptions of learning as identified by Marton et al. (1993).

(iii) Category Distribution Across the Sample of the Participants

In most cases, the quotes, taken from one individual, were assigned to more than one category (for example, quotes from Jody were placed in categories B, C and D and quotes from Andy in D and E). In addition, more than one category of description was assigned to the participants who showed no consistency between the initially described visualisation and the description given to the implemented supplementary sheets (see Table 8.6. and Table 8.7.). Although individuals were assigned to more than one category (e.g. Jody’s quotes were found in categories B, C, and D) only the prevalent

category (e.g. how many quotes from Jody were found in each category) was considered in assigning the category distribution across the participants. The results obtained were separated according to the gender of the participant and are shown in Table 8.10.

Table 8. 10. The distribution of the categories across the sample of the participants.

Category	Participants					
	All		Males		Females	
	No/ of 25	%	No/ of 13	%	No/ of 12	%
A1	3	12	0	0	3	25
A2	1	4	1	7.7	0	0
B	3	12	1	7.7	2	16.7
C	12	48	7	53.8	5	41.7
D	4	16	2	15.4	2	16.7
E	2	8	1	15.4	0	0

Oversby, 1999

The results in Table 8.10. suggest that the visualisation as described by category C, was portrayed by the most participants involved in this study (48 %). However, the results also suggest that another 24 % of the participants showed the developed visualisation (categories D and E), the male participants contributing in both D and E categories, the females only in category D.

Because of the small number of participants, the findings in Table 8.10. simply demonstrate the profile of the participants involved in the study and cannot be generalised.

(iv) Discussion

The different outcomes in student visualisation of molecules are linked to the use and understanding of multiple representations and visualisation skills, but also could be linked to, and be a consequence of the way in which chemistry concepts have been taught (see also Oversby, 1999 and the discussion later).

(a) *Visualisation – The Use of Multiple Representations*

Two aspects of the multiple representations are addressed here:

- its relation to the chemistry understanding;
- its relation to the visualisation ability.

The students' visualisation was viewed through Johnstone's assertion (1991; 1999; 2000) that understanding of chemistry means the integration of the understandings across the microscopic, symbolic and macroscopic nature of chemistry.

The results obtained showed that some participants were competent at visualisation in which they integrated multiple representations of the molecules and showed ability to switch between different representations and use more than one representation/model spontaneously if necessary (categories E and D). Bodner and Domin (1998) investigated the role of representations in problem solving in chemistry and found that students' ability to switch from one representation to another distinguished successful students in organic chemistry from those who were not. They also found that successful problem solvers constructed significantly more representations while solving a problem than those who were not successful.

The ways in which students visualise molecules and their ability to apply multiple representations are connected to 3D visualisation or spatial ability. A study by Pribyl and Bodner (1987) revealed that high spatial ability students tended to employ multiple drawings and structures ensuring the more complete, correct and more accurate portrayal of the problem being investigated (categories E, D, C). Low spatial ability students have been described as more likely to draw an incorrect structure (category A). Bodner and Domin (1998) argued that disembedding the relevant information from the statement of the problem and restructuring or transforming the problem into one the individual understands involves similar stages to those in the spatial domain. According to Bodner and Domin, in solving problems the student must convert the string of words into some internal representation that can be manipulated in an effort to solve problems.

In this study, the students who were not able to draw correct structures were assigned to category A. Their diagrams represent only a fragmented or incomplete form of the representations used (A1 and A2) and may be used as an indicator of students' poor spatial abilities. These students showed confusion in their description, some commented

was “hard to visualise” and did not demonstrate that they have processed the information collected from chemistry instruction over time holistically. The ability to perceive relationships and process information holistically has been described as an essential characteristic of spatial ability (Pribyl & Bodner, 1987). The visualisation assigned to category E, with supported description and diagrams may be used as an indicator of students’ high spatial abilities.

(b) Student Visualisation – Reflection of Chemistry Instruction

In this study the participants’ visualisation reflected the students’ attempts to describe molecules on the basis of what they were taught at high school (linear structures) or university (space filling models) or what would be an appropriate visualisation for ‘university standards’. Some of those who still preferred to visualise molecules in a way they were taught at high school could not resist apologising for visualising without using 3D representations (space filling models) that were used in lectures at university. The results suggest that students’ visualisation mostly mirrored the ways chemistry was taught to them. The quote of Romy given to support the conceptualisation assigned to category D can be used to support this discussion as well:

I think the representation we have and about how you think about molecule, depends on what you learn about the molecule, like if you learning about its reactions, you like just draw like a skeletal structure, but if you are talking about um, its electrons or the shape of this molecule you might use some other structures, yeah .. (Romy)

This is in agreement with the claims found in the literature (Laws, 1996; Ramsden, 1993; Shepard & Gilbert, 1991), which suggest that students’ science conceptions and their learning approaches are influenced by the ways in which knowledge is structured and presented to them. According to Ramsden (1993) different teachers frame different curricula for students and in a real sense, they teach different things and students learn different things from them. Different teaching strategies resulted in student visualisation mostly based upon the knowledge structured and presented to them at high school. Some students tried to include as much as possible from the knowledge that was structured and presented to them at university. The time spent with the knowledge structured and presented to them in one or another way has been identified as an important factor influencing student visualisation.

The results of this study showed that most of the participants had not yet developed a

high level of competency in molecular visualisation (category E). Gabel (1999) discussed how chemistry instruction predominantly uses the most abstract symbolic representations and how the symbols that chemists use are often ambiguous. Symbolic structures were the ways most participants employed in their description of visualisation with fewer recalling the physical ball and stick models. According to Gabel (1999) a student must be capable of associating particles with models or analogies in order to understand the microscopic nature and that models must be associated with symbols. Gabel (1993) suggested that chemistry could be taught and understood better if the kind of instruction that students receive ranged across the threefold nature of chemistry (according to Johnstone, 1991; 1999; 2000, microscopic-macroscopic-symbolic). Gabel highlighted an effective role of the particle nature of matter in helping students to make connections within the threefold nature of chemistry.

It seems that only the integration of different ways in which macro-micro-symbolic links are made can lead the student towards better understanding. As the threefold nature of chemistry can be interpreted in more than one way and as teachers in their lecturing, either unconsciously or deliberately, move between the symbolic, the microscopic and the macroscopic nature and the interpretations within them (often not made explicit), quite often students fail to integrate these different interpretations into their own conceptual frameworks. This might lead students to form a fragmented and incomplete view of chemical phenomena (Gabel, 1999); such was the visualisation identified in category A, in which many parts did not seem to fit together in students' explanations, although to them it might seem that everything did fit together. According to Lemke (2002) students should be taught not only about the concepts but also about any representation/model (symbolic versus microscopic for example) used to represent the concepts and how to see something that is very 'obvious' to the teacher who uses them in his/her instruction. Bodner and Domin (1998) discussed that students' notes seem to be copies of what the instructor wrote. In spite of the apparent similarity, there is a fundamental difference between what the instructor and what many of students understand by what is written down. The instructor writes *symbols* which may to him/her represent reality, and too often, students write letters *and numbers and lines*, which have no physical meaning to them, leading to a fragmented visualisation (identified in category A). According to Vygotsky's sociocultural perspective, in such situations a lack of enculturation into meanings has occurred.

Chemistry instruction given to the first year undergraduates at Massey University in 1999 involved a description of phenomena at a microscopic level extensively. Ball and stick physical models but also computer generated representations of both ball and stick or space-filling models often supported the instruction given at lectures. All these teaching aids aimed to proximate the 3D shape of molecules and help students' visualisation. In addition, computer-modelling programs such as Spartan were used to illustrate the dynamic nature of molecules (e.g. showing atoms vibrating, bonds rotating and changes in atoms' distance or bond length within the molecule; intermolecular attraction or repelling between molecules were also demonstrated). Dynamic microscopic models contributed to students' visualisation assigned to categories D and E. The ways of visualising in which the participants discussed intermolecular forces and connected them to physical properties of the substance (i.e. melting points) were the identified students' constructs, which according to Johnstone (1991), integrated microscopic and macroscopic levels. However, most participants talked about visualisation based on the symbolic structure because they were taught that way at high school as opposed to the visualisation of what some participants described as 'fluffy balls' taught at university (student visualisation that was assigned to categories C and B). The time spent and the experience gained over the years with the structures being taught at high school (linear structures, Lewis structures) made the participants feel familiar with them. The 'fluffy balls' introduced at university were experienced as less familiar regardless of the fact that the students were aware that "they might represent a better truth of what the molecules really look like". This is in agreement with both Lemke (2002) and Johnstone (1999) who argue that only the experience in dealing with science might enable the learner to integrate different languages (verbal, symbolic etc.) or levels of chemistry and see 'what is obvious' in the representation used.

(c) Student Visualisation – A Dimension of Different Approaches to Learning

The qualitatively different ways in which the participants of the study visualise molecules can be related to different approaches to learning. This is in agreement with what was suggested by Davies Burns (1997) and Entwistle (1997).

The multiple approaches combine a surface approach and memorisation necessary to cope with the course requirements, a deep approach and seeking for an understanding of the ideas for oneself, but also a strategic approach to achieve the highest possible marks.

All these approaches combined contributed to the development of student visualisation.

Students described that memorisation helps in learning the concepts of isomers and the terms describing them. The role of memorisation in learning about stereoisomers, for example, can be explained as an additional approach to achieve meaningful learning (Marton et al., 1997 described it as a relationship known as the “Chinese paradox”, while Biggs, 1999, indicated the role of memorisation in, for example, learning formulae).

The approaches to learning the participants talked about in the present study and the student visualisation of molecules with its 3D aspects distributed to the categories A to E represent the outcomes which are related to one another and which both contribute to learning of stereochemistry.

(v) Conclusions

Visualisation of molecules is related to the student understanding and managing the different representations used in chemistry instruction. The students' ability to apply the multiple drawings and correct representations might be related to their spatial ability, but also to their approaches to learning.

The stereochemistry tutorial developed in Study Two employed different representations. However, the results obtained in this study suggest that the representations employed in the tutorial do not match those which the students most readily employ in describing visualisation of molecules. This might have influenced the student-tutorial interaction and particularly student success with the tasks involving more complex molecules and should be considered in the tutorial revision. One of the aims of the next study will be to check if the students' lack of competency in solving stereochemical problems was caused by a lack of appropriate representation being provided to them by an expert.

8.4. VISUALISATION versus MACROSCOPIC SAMPLE OF THE SUBSTANCE

8.4.1. Analysis

Having drawn out and described the ways in which students visualise molecules, the students were shown a bottle containing 2-butanol, which is a colourless liquid. The bottle was clearly labelled. The participants were asked to relate their description and drawings given before, to the contents of the bottle. These participants' responses contributed to the ways in which they described visualisation of molecules and were considered in assigning student visualisation, but were not initially explored in detail (see Table 8.5.). In order to answer the Research Question 3b, the analysis here was specifically focussed on the students' responses when confronted with the colourless liquid and asked to relate their visualisation of molecules to the macroscopic sample of the substance.

Of the 25 interviews, all individual responses to the appearance of the colourless liquid, together with any other description related to the macroscopic nature of chemical compounds, were extracted and analysed separately, but still in the context of the whole interview. The students' responses have been analysed not only on the basis of their descriptions, but also on their distinct emotional reactions. These ranged from surprise to confusion, as shown by changes in the voice tone, big pauses or a long time required to respond compared to the overall flow of the interview. Some students were able to make no comments at all (field notes).

Step 1 – A range of meanings

The quotes were read repeatedly and compared to each other. The rereading of the students' verbal responses when accompanied with the emotional responses (written in the form of the researcher's field notes) enabled the researcher to identify the meanings that appeared in each quote. Similar meanings were found in the quotes originating from different participants. The quotes allocated to different meanings formed the pile or 'pool of meanings'. Table 8.11. shows the different meanings named according to what the participants themselves highlighted in their quotes.

Table 8.11. The different meanings that emerged from the participants discourse in the initial step of the analysis process.

Meaning /Description	Examples (quotes)
▪ <i>Macroscopic – microscopic association/</i> participants either talked about ball and stick models or they pointed at the model they built during the first phase of the interview.	“It’s got lots of these molecules in it “ [pointed at the ball and stick model in front of her, she had made earlier] (Kay) “In clear liquid there are little balls and sticks. They would be so tiny that you can’t really tell what it is made of.” (Ken)
▪ <i>Movement/</i> different words were used by the participants that suggested movement of the particles – bouncing, floating, moving etc.	“Everything is moving around ..” (Ben) “Huge amount of 3D molecules move, all stacked together in there” (Mark) “I imagine them as very, very tiny in there somewhere, lots of them sort of floating around.” (Romy) “Slightly attracted to each other, which makes them a liquid.” (Paul) “Molecules slide around. Not held firmly. Weak interactions are being continuously broken and re-established.” (Andy)
▪ <i>Gas-liquid-solid/</i> states of matter and the particle distribution were present in student discourse.	“Gas molecules further apart, solid tightly packed, liquid more freely spaced.” (Amy) “Further apart in the liquid than they would be in the solid.” (Mark)
▪ <i>Looks like water or any clear liquid /</i> colourless liquid in the bottle looked like water.	“Somehow looks just like water.” (Tammy); “Could be water, probably you could drink it.” (Ben)
▪ <i>Needs testing - link to chemistry labs /</i> students talked about for example colour changes or doing the tests for alcohols.	“I, sort of, just have to believe that clear liquid is 1-butanol, could be water. Can’t be sure it’s 1-butanol without testing.” (Dan) “Test alcohols to see if they are primary, secondary or tertiary.” (Carl)
▪ <i>Chemical structure/Formulae/</i> students talked about the chemical structure and discussed reactivity.	“How it is to react is to do with its formulae.”(Tammy) “I would think it has gone into solution, dissolving, sort of bonding with water.” (Thai)
▪ <i>Hydrogen bonding/</i> a sight of colourless liquid initiated some participants to talk about hydrogen bonding	“There’s definitely H-bonding.” (Erica) “Um, the fact that it’s a liquid shows that there’s definitely a hydrogen bonding between the molecules.” (Eddy)
▪ <i>Functional group as identifier/</i> students talked about hydroxo group or – OH group	“Test the properties of OH group.. You can’t see them, but you can test for their properties, you know, because of the OH group there, yeah ..” (Paul)

▪ <i>Label/ label on the bottle informed on what was in it.</i>	"The only link is by the name" (Marry); "... if that label was not there you wouldn't really have a clue" (Tammy).
▪ <i>Integration of different chemical ideas/ a sight of colourless liquid initiated student to integrate many ideas with different meanings.</i>	"Sort of 3D molecules move, very huge amount of them, all stacked together by some relatively weak intermolecular forces which keep them in a liquid, ..., there is a dipole-dipole and I don't know quite lot of what OH could do and there, I suppose it's just a liquid, just as more functional atoms are further apart than it would be if there were solid but not as far apart as in a gas and a lot of them are free to move around. " (Mark)
▪ <i>No chemical ideas associated/ Students' responses to a colourless liquid in which no chemical ideas were associated were separated.</i>	"I don't have to think what this molecule looks like, I just need to use butanol - I wouldn't think of anything else. I'd be just thinking of what I need to know. Depends on the situation. What way to use. " (Thai)
▪ <i>No clear response/ The responses to a colourless liquid in which students declared how they cannot make any association or the irrelevant responses in which students talked of everything mixed up, like guessing, no one idea was clearly explained.</i>	"I am thinking of which one, a tiny little part of it, a part of that liquid I think of these that forms, of the composition, that makes up the composition of liquid, so one mole of one of these diagrams, I think a bit more, I like if I could see a bit of more of particles of thing, one mole of particles, ..., depends on the concentration, how many moles per litre .." (Meg)

Pavlinic, 1999

Step 2 – Differentiation between the meanings

In the second stage, the differentiation within and between the meanings was employed. The meanings were analysed in terms of similarities and differences and the relationship between them. For example, the meaning embodied in the group of quotes named *Movement* and *Gas-liquid-solid* has been assigned together with the meaning *Macroscopic – microscopic association* because a macroscopic aspect of the phenomenon has been discussed in each of three meanings. The meaning *Looks like water or any clear liquid* was assigned together with the meaning named *Association with chemistry laboratories* as in both students made associations to other real phenomena. That resulted in the merging of some of the previously identified meanings. The quotes in one merged meaning had some common description to each other but they differed from those in the other.

The results of this classification are given in Table 8.12. The merged meanings comprise the same focus of the students' awareness and were numbered, with the higher number attempting to demonstrate better student ability in communicating diverse

chemical ideas with the sight of colourless liquid.

Table 8.12. A summary of the step of the analysis, in which different meanings were analysed according to similarities and differences between them.

Merged meaning	Previously identified meaning/s merged	Description
1	No chemical ideas / No need to associate the two / Irrelevant responses	This meaning includes irrelevant responses, responses in which students could not make any comment and responses in which they described that there is no need to link the two.
2	Label	The meaning which includes description about the label or name as the only link between the colourless liquid and their visualisation
3	Looks like water or any colourless liquid / Link to the chemistry laboratory.	This meaning includes responses in which students linked the colourless liquid to other observable phenomena (water, laboratory tests)
4	Structure / Functional group as identifier / Chemical reaction	This meaning includes responses in which students linked the colourless liquid to symbolic models such as formulae, structure with OH group, equations. Chemical reactivity of a liquid was articulated through symbolic representations.
5	Macroscopic-microscopic association / Movement / Gas-Liquid-Solid / Intermolecular forces (Hydrogen bonding)	This meaning includes responses in which students linked the colourless liquid to microscopic models, static or dynamic).
6	Integration of different chemical ideas	The more developed descriptions involve integration of symbolic and microscopic awareness, (movement, discussion of the particle distribution, attraction forces between particles) and discussion about the chemical and physical properties of a liquid.

Paolink, 1999

Step 3 – Categories of description

Next, the meanings embodied in students' quotes were re-analysed in order to describe a student's ability to associate the 'real' liquid with his/her previously described visualisation when asked the question: "How would you relate your description and/or drawings of 2-butanol to the content of the bottle containing a colourless liquid and labelled 2-butanol?"

The results in Table 8.12. were close to representing categories. Merged meaning 1, with no chemical ideas associated or with irrelevant responses, was assigned to category A. Meaning 2, in which students talked about a label as the only link between their visualisation and a liquid in a bottle, was assigned to category B. Merged meaning 3, in

which the link was made to other real phenomena, was assigned to category C. However a clear borderline was not identified between meanings 4 and 5 shown in Table 8.12. It was identified that both ways of description can be equally categorised (sub-categories of category D), whether the participants linked the colourless liquid to the symbolic representations or to the microscopic models used earlier to describe their visualisation of molecules. The discourse in meaning 6 was assigned to category E and was clearly distinguished because of the integration of many ideas, and both symbolic and microscopic associations were found in a rich description. The categories were placed at specific levels in a logically structured hierarchy. The hierarchy is constituted with respect to complexity and inclusivity in that categories of a higher order subsume aspects of the phenomenon recognised in the categories of a lower order.

Step 4 – Fitting the categories into the macro-micro-symbolic triangle

Finally, the meanings that were formed and named according to the chemical ideas associated to the sight of a ‘real’ liquid were checked to ascertain whether or not they support the theoretical framework of Johnstone’s macro-micro-symbolic triangle of chemistry, previously discussed in connection with visualising molecules.

All students’ responses, sorted according to different meanings in the ‘pool of meanings’, were then analysed in terms of the structural and referential aspects of students’ ability to respond and describe the phenomenon. The integration of the macroscopic corner (2-butanol as a liquid) with the other two microscopic-symbolic corners (prevalent in students’ description of 2-butanol – theme one) within the Johnstone’s triangle (1991; 1999; 2000) was used as a referential aspect of analysis.

8.4.2. Students Relate Their Representations of a Molecule to a Macroscopic Sample of the Substance – Results

The categories of description represent the outcomes of the phenomenographical approach that was employed in the analysis of the participants’ discourse, in which students applied diverse chemical ideas to a ‘real’ liquid sitting in a bottle on the bench.

Most of the students experienced surprise or confusion – a schism – even a shock when confronted with this colourless liquid labelled 2-butanol, as if they had not been expected to be shown something like that or asked to think about it. The researcher

noted things such as a change in the tone of voice, a big pause, a long time required to respond or being unable to make any comment at all (field notes). Although these responses contributed to all results, their significance was not apparent in the outcomes given in a form of categories of description that were based on the analysis of students' description only and will be addressed later in discussion.

(i) Categories of Description

The resulting categories of description that were hierarchically ordered with an increasing level of student ability to articulate the 'real' liquid in a bottle with the visualisation of a molecule previously given, are shown in Table 8.13.

Table 8.13. The hierarchically ordered categories of description with the allocated meanings, showing increasing students' ability to associate the macro nature of 2-butanol (liquid) to their visualisation of the 2-butanol molecule described earlier.

Category/ Referential aspect	The meanings (according to the chemical ideas in student discourse)	Structural aspect /Focus
A1 - No association A2 - No need to associate it	No chemical ideas associated Irrelevant association No need to associate it	Either no chemical ideas associated or association with no clear focus, or no need to associate
B - Link by the name	Name or label	Link by the name or label
C - Association with other real phenomena	Looks like water or any clear liquid Association with chemistry laboratories	Association with other real phenomena; focus within the macro nature of chemistry
D1- Association with structure	Chemical structure/ reactions Functional group as identifier (Movement)	D1 - Association with structures; focus on macro -symbolic link
D2 - Association with micro models	Macroscopic-microscopic association Gas-liquid-solid Movement Hydrogen bonding	D2 - Association with the microscopic nature of a chemical compound; focus on macro – microscopic link
E - Developed integration	Integration of different chemical ideas	Developed integration involves more comprehensive explanation with different aspects being discussed (symbolic and micro, intermolecular forces etc.)

Payline, 1999

Two different subcategories have been identified in the lowest **Category A**; A1- No

association (meanings *No chemical ideas* and *Irrelevant association*) and **A2 - No need to associate**.

In the subcategory A1, the students responded that they could not make a link between the colourless liquid in a bottle and the structures/models they had talked about or drawn earlier. This subcategory also included the responses in which students talked about different and quite often irrelevant ideas mixed up; none of the chemical ideas were clearly understood or linked to the liquid.

In the subcategory A2, they described no need to associate them together. For example, Tammy described that her approach is not to put the 'real' chemistry and chemical equations or structures together. Instead it is the laboratory manual book that brings the two together:

... it's only 2-butanol in the chemistry labs so you go and look on the bottle and find 2-butanol and then like in inside of the lab books we have the little diagrams of what the structure would look like and I never really pictured trying to put them together (Tammy)

Category B - Link by the name or label. Four responses were grouped in the meaning *Label* in which the students talked about the name, word or label as a connection between the 'real' liquid labelled 2-butanol on the bench and the ways of visualising molecules they described earlier. Dan elaborated the role of a label in distinguishing one colourless liquid from the other:

Well, when I said 2-butanol, I mean 2-butanol, I know that's what's in there, but if you give me this liquid without a label, it could easily just be water or any clear liquid ..(Dan)

On the other hand Jody described that the name or label is the basis that you start from:

I don't visualise it at all as a whole bunch of these little atoms or molecules, sitting out there, I just see it as a clear liquid and I read the label and then I think oh, OK this is what it's gonna look like, following the label. (Jody)

Rudy's description involved the motion of label or word inside the colourless liquid:

... when I have a good look, like at the product, I actually have the word 2-butanol floating around inside liquid. I don't actually picture the molecules floating around in the liquid. I actually think from the word back put into this [pointed at the liquid] (Rudy)

Category C - is the category named **Association with other real phenomena** (within the macro nature of chemistry). In this category, the students tried to describe the 'real'

liquid in a bottle by associating it to another liquid (water) or to other chemistry-related observable experiences they had experienced (responses were sorted from the meanings *Looks like water or any clear liquid* and *Link to the chemistry laboratory*).

Looks like water or any clear liquid - A number of students associated a colourless liquid in a bottle to the well known other colourless liquid from the ‘real’ world, water. For Tammy the colourless liquid “Somehow looks just like water”, Ben even added: “Could be water, probably you could drink it.” Some students adopted a strategy of comparing the property of the liquid in the bottle with the properties of water:

What I see is just clear liquid, might be slightly thicker than water (Jody)

Link to the chemistry laboratory - a meaning with the students’ quotes in which they described testing, such as experienced in their laboratory classes, as a way to identify the liquid in the bottle. Such descriptions were assigned to the association within the macro, observable nature of a chemical compound as well. A number of students, such as Dan indicated how they “can’t be sure it’s 2-butanol without testing.”

Students who thought of chemical tests and linked the colourless liquid to the chemistry laboratory revealed the ways they experience chemistry instruction in general:

Same problem in the lab; It’s all going well on paper but when you see it, it is quite different. (Jody)

At school we spent more time doing this with theoretical molecules, rather than experiments. (Ken)

and laboratory classes:

Do a bit of chem lab, adding to this, it changes colour and end up with a few calculations. (Ben)

Category D – Association induced by symbolic structures or 3D ball and stick models that students had made - is the category with quotes collected from the majority of the participants. A colourless liquid was associated to something already seen, known, or just what was handy at the time (in this case students’ drawings and/or the ball and stick models they built were in front of them). It was highly likely that students would make these associations as they were asked to relate the ‘real’ liquid to what they already had said, drawn or made. The ball and stick physical model and the various symbolic representations /structures in the form of student drawings were in front of the student when the student was confronted with a colourless liquid in a bottle.

Two different, but parallel subcategories (associations) have been identified. The first subcategory D1 is based upon students' attempts to explain the 'real' liquid through their understanding and visualisation of molecules earlier described and represented in different symbolic forms (formulae, equations or structures with functional group). The other subcategory D2 is based upon the students' attempts to explain the 'real' liquid by linking it to the microscopic representation or when, in trying to explain the behaviour of a liquid, they applied either their understanding of the particle nature of matter or the ball and stick models they have built before.

D1 - Association with structure (macro - symbolic)

In subcategory D1, the students tried to elaborate on the liquid in the bottle labelled 2-butanol through its symbolic representation (structure of a chemical compound). The students' quotes from the meanings *Chemical structure (reaction)* and *Functional group as identifier* contributed to this subcategory. Two levels of the associations have been identified; the first did not include any additional description.

Structure/Chemical reactions – The 'real' liquid initiated some participants to acknowledge how knowing symbolic representation (chemical structures or equations for chemical reaction) is helpful in understanding chemical reactions that take place in the laboratory and observable changes can be better understood:

If you can visualise what its structure on paper is you can understand reactions better... Unless you know what it's doing on paper its just changing from green to orange. (Dan)

Similarly, from the meaning ***Functional group as identifier*** – the participants talked about a type of organic compound, such as Kay "It's a liquid, it's an alcohol", or Carl who recalled the functional group of alcohols and the tests "to see if they are primary, secondary or tertiary". The alcohol functional group (-OH group) was recognised from the symbolic chemical structure and was recalled as OH group (e.g. Mark wondered "what OH could do").

In addition, Rudy (the quote below was placed in the meanings *Movement*) could not find an appropriate symbolic explanation for the movement of the liquid labelled 2-butanol. Instead, she used a model of analogy in which symbolic H^+ ions are moving in acids:

I have the word 2-butanol floating around in the bottle. I don't actually picture the molecule floating around, only the word. For acids I see H^+ floating

around. (Rudy)

In the next level of this subcategory, the liquid of 2-butanol in a bottle prompted students to assign physical or chemical properties on the basis of chemical structure. Ben for example, discussed the properties of 2-butanol in relation to the structure:

I would say, comparing it, yeah, cause is pretty runny, is pretty fluid, since it is only a short chain, it's only got one bond ... (Ben)

To Jack, the symbolic hydrogens provoked him to talk about hydrogen bonding in the liquid, while Paul mentioned that it is possible to “test the properties of OH group”.

Two students talked about the chemical reactivity of a compound in relation to the structure/formula:

You wouldn't know without a label.. Not until you see the structural formula... How it reacts is to do with its formulae (Tammy)

If you can visualise its structure on the paper you can understand reactions better. Unless you know what it's doing on paper its just changing from green to orange. (Dan)

Although the formula is not responsible for the reactivity (as Tammy stated), but rather the reactivity is rationalised through the formula (as Dan described it correctly), in this sub-category, an explanation of the symbolic representations was employed in an attempt to link a macroscopic nature of the substance with the students' visualisation.

D2 - Association with the micro nature of a chemical compound

In subcategory D2 the students associated the macro appearance of the substance to the microscopic representation employed in their visualisation of molecules; they also recalled the particle nature of matter, which was often used in the chemistry course.

Most of the participants had a ball and stick model of 2-butanol sitting in front of them, as they had made it before being confronted with the colourless liquid in the bottle labelled 2-butanol. When asked to describe the way they relate liquid to their previous description, some made links to the models still in front of them.

The students' quotes assigned to the meanings *Macroscopic-microscopic association*; *Movement*; *Gas-Liquid-Solid* and *Hydrogen bonding* contributed to two distinctive associations in this subcategory (similarly as in the subcategory D1). One association can be described by the conception of **static** or fixed ball and stick model. The responses in this category include those assigned to the meaning *Macroscopic-*

microscopic association, however some students added an additional dimension, such as particle distances or attraction forces, which were selected from the meanings *Gas-liquid-solid* and *Hydrogen bonding*.

The quotes such as given below support the ***Macroscopic-microscopic association***:

I can just picture all these little, these sort of things inside the liquid. [pointed at the ball and stick model] (Erica)

For Eddy, a molecule in the form of a model seemed pretty real (visible) on the bench: “No way of telling what the atoms look like by looking at a bottle of 2-butanol. On a large scale it looks like a liquid and on a small scale it is like a molecule.”

Some students made clear distinctions between the two, such as Thai: “Wouldn’t you said it was 2-butanol in the bottle. I would never think at the molecular level.” Some predicted the interactive forces between particles (intermolecular forces), but without detailed explanation:

When I try to think of a liquid, you cannot see them but there are a lot of atoms, I suppose they are interacting. (Lee)

Gas-liquid-solid - This meaning involved descriptions in which students focussed on liquid as a state of matter and comparisons were made with the other states of matter. Students compared the distance between the particles in a liquid with the distance between the particles in a solid or in a gas state of matter:

Because they are in the liquid state they are floating around and stuff. In a solid they would be fixed, in gases further apart. (Erica)

Although the awareness of hydrogen bonding was mentioned earlier as an indication of the macro – symbolic association by a few participants, the quotes from the meanings ***Hydrogen bonding*** indicate that some students added hydrogen bonding as intermolecular forces to their macro – micro association:

There are lots of these [models] in a bottle with hydrogen bonding together. (Steve)

Further elaboration of what might be happening with the particles in liquid state involved an additional dimension, movement (added from the meaning named *Movement*), which contributed to a **dynamic** conceptualisation of the phenomenon.

Movement - Many students tried to associate the movement of molecules with the liquid in the bottle:

Lots and lots of molecules colliding, attracting and repelling. (Kay)

Liquid solution they are trying to move around a fair bit, they are knocking each other away. (Carl)

The students' quotes that were allocated to the higher categories quite often can be equally used to illustrate different meanings (higher categories subsume aspects recognised in lower categories). The meanings are interwoven, particularly within the same category. In the subcategory D2 for example, the student descriptions of dynamic motion (classified in the meaning *Movement*) illustrate at the same time understanding of the other meanings (*Macroscopic-microscopic association* and *Gas-liquid-solid*). The quotes of Amy, Mark (see Table 8.11.) and Erica given earlier as support for the meaning *Gas-liquid-solid* illustrate how the students, when talking about the liquid particles as being "more freely spaced" added an additional dimension of dynamic motion of the particles which "are floating around" or "bouncing around". The quote below is similar to those mentioned above:

Because it is a liquid I guess, molecules are floating and go together, um if there would be a gas I would expect them to be, you know, quite far apart, um, in liquid they are bouncing around I guess and I just thought they would be closer to each other (Romy)

When a description of a lot of constant movement was combined with a description of differences between the particle distribution in gases, liquids and solids, the students' descriptions become more detailed and more sophisticated:

As soon it's a liquid I imagine it .. most kind of quite vibrating particles, as well as in a solid you know, there will be no vibrations and so ever, but it's not a gas either, so it differs .. (Dug)

I just think of like thousands of them in the middle of the bottle, you know moving around and stuff .. Cause it's a liquid and they tend to move around in a bottle, I think if it was a gas it would move faster, yeah the molecules are moving, yeah (Cara)

The highest identified **Category E - Developed integration** is a category which involves an integration of different meanings and a very detailed description.

Andy was a student who mentioned that 2-butanol is a liquid before being confronted with a bottle containing colourless liquid, labelled 2-butanol. When shown the bottle of 2-butanol his response was rich in description and involved different aspects being articulated together, for example properties and the structure including the nature of

intermolecular forces between molecules:

OK. Um, because it's liquid the molecules are able to slide around, pass each other. Um, there is a weak interaction between the molecules, not holding the molecules so firmly that the entire mixture of molecules is held together so firmly that they can't move around and pass each other. So the weak interactions between the molecules are constantly being broken and re-established. So um, at any time this one molecule in a liquid is moving around, um, and is changing which molecules they are in association with. So it might be associated with the molecules at the top of the jar one minute and the next minute the molecule is associated with the other molecules at the bottom of the jar, just slightly passing each other, moving around. (Andy)

Another example is Mark's description of his dynamic conceptualisation of a liquid which involved many integrated meanings - the particle nature of matter, attractive forces and movement of molecules, comparing the distance of molecules with those in a solid state of matter. In addition, he had the symbolic OH group and its properties in mind (his quote is given in Table 8.11).

The integration of many meanings in category E led to a developed association between the 2-butanol as a liquid and the symbolic (structural, 2D) and the microscopic (3D models) awareness present in visualising of the 2-butanol molecule (students were shown liquid at room temperature and were not tested on how the liquid state changes depending on the temperature).

Furthermore, the quotes in this category contain student descriptions that involved awareness of physical or chemical properties of the 'real' liquid they saw. For example, some students talked of melting point or viscosity, others talked about reactions in which the colour change occurs (e.g. reactions of primary, secondary and tertiary alcohols). Being able to articulate physical and/or chemical properties of a compound (something that we experience in a real world, something that we see, smell, touch, observe or measure) demonstrates a more developed conceptualisation of a chemical compound.

The students who were able to associate 'real' liquid within the macro and between the macro and other dimensions of chemistry (symbolic or micro) were aware of the properties, either physical or chemical.

According to the structural aspect, the identified categories, as described above (category A - category E) show the hierarchical order with an increase in the student's ability to describe, link or associate the 'real' liquid to previously described mainly

symbolic and/or micro visualisation of chemical compounds.

The student’s ability to articulate (associate) the ‘real’ liquid or macro dimension to the micro and /or symbolic dimensions of the phenomenon (viewed through Jonhstone’s triangle) increased from category A to category E.

(ii) Category Distribution Across the Sample of Participants

Apart from the results given in a form of the categories of description, additional analysis aimed to inform about the category distribution across the participants.

The quotes were taken from the categories back to the individuals and the categories from which the quotes were taken were allocated to individual students. If the data from one participant contributed to more than one category (most of them did), only one category, to which most quotes were allocated, was taken into account. For example, the quotes in the meaning that was assigned to Category B (link by the label) derived from more than one participant. However, only one participant was counted to this category. The prevalent responses of the other participants were assigned to the categories other than B, though they contributed to category B as well.

The results obtained were separated according to the gender of the participants and are shown in Table 8.14.

Table 8.14. The distribution of the categories across the participants.

Category	Participants					
	All		Males		Females	
	No/ of 25	%	No/ of 13	%	No/ of 12	%
A1	4	16	2	15.4	2	16.7
A2	1	4	0	0	1	8.3
B	1	4	0	0	1	8.3
C	3	12	2	15.4	1	8.3
D1	3	12	0	0	3	25
D2	11	44	7	53.8	4	33.3
E	2	8	2	15.4	0	0

Pavlinic, 1999

The results in Table 8.14. suggest that the responses of 44 % of the participants were

allocated to category D2 in which the sight of the colourless liquid prompted participants to recall and talk about some aspects of the microscopic world of chemistry. The contribution of the male participants was higher than the contribution of the female participants in the category D2 (53.8 % and 33.3 % respectively), also the responses from some of the male participants were assigned to the highest category E. The responses allocated to the lowest categories A1 and A2 derived from five different participants. Although university entry anticipated all students having an appropriate background in chemistry (7th Form/Bursary Chemistry), and they were all exposed to the same lectures, the results show that the first-year undergraduates also varied in their abilities to convey the 'real' liquid and the visualisation of molecules described earlier.

Because of the small number of the participants, the findings in Table 8.14. demonstrate the profile of the participants involved in the study and cannot be generalised.

The findings of this phenomenon contributed to the ways of visualising molecules, but were used only as additional data in assigning student visualisation (see Table 8.5.). When the findings given in Table 8.14. were compared to the findings given for category distribution of visualising molecules (see Table 8.10.), a close agreement was found for the participants allocated to the lowest and highest categories. The same participants who were allocated to the lowest category A (subcategories A1 and A2) in visualising molecules were allocated to the lowest category A (subcategories A1 and A2) in this analysis as well. In addition, one participant who was not able to comment on the real liquid was added into the lowest category A. One of the two participants who were allocated in the highest category E (Table 8.15) demonstrated visualisation allocated to the highest category E, the other was allocated to category D.

The participants with responses found in the categories B, C and D (D1 and D2) demonstrated visualisation as described by the categories B, C and D respectively. More than one way of visualising molecules without (category C) or with the integration between them (category D) were the ways of visualising molecules for most participants. In describing the macroscopic nature of the substance in relation to the ways they described visualisation of molecules those participants were assigned to the categories C and D (subcategories D 1 and D2).

(iii) Discussion

When confronted with the colourless liquid of 2-butanol and asked to relate it to the

ways they had visualised a 2-butanol molecule, the students made a diverse range of associations. These different responses (also called associations) were placed in the hierarchical order of five categories of descriptions (from A to E) with increasing sophistication of the description or student ability to integrate different chemical ideas with the sight of a 'real' liquid. Awareness of the properties of a chemical compound has been found in the descriptions allocated to the categories C and D and E.

Up to the point of being faced with a "real" liquid in a bottle, labelled 2-butanol, the students' descriptions were mainly of the abstract nature (symbolic and/or microscopic). Being shown a 'real' liquid was a moment when it might be thought that the students were perfectly poised to make the macroscopic – microscopic – symbolic links (Gabel, 1993; Gabel, 1999; Johnstone, 1991; Johnstone, 2000), that are expected of a trained chemist.

The participants' ability to articulate, switch and integrate these three aspects of chemistry was the aspect of analysis explored in this part of the study. One question was whether there was any link between how well students appeared to operate in the microscopic and symbolic worlds of chemistry knowledge and the ability to relate this theoretical world back to a physical substance.

From all the results obtained in this part of the study, three insights emerged:

Firstly, the students' emotional responses to seeing the 'real' liquid were not specifically assigned to any of the identified categories, but contributed to each of them. The verbal responses such as "Um, it's a good question" (Martin) or "Um, I find it very hard 'cause this is a very awake and very visible" (Cara) or

Um, all the different representations, how can we bring them together to 2-butanol as a liquid .. um ..

Yes, but, if I have never seen 2-butanol before and you try and teach me on paper ..

Yeah, if I have never seen 2-butanol before, how am I meant to tell it is a liquid? How am I supposed to bring everything together to represent that it is a liquid? (Carl)

suggest that students had not expected to be asked such a question. Even if it appeared that they were happy with the knowledge-based world of chemistry that they operated in before being confronted with the colourless liquid, the appearance of the real substance often caused confusion and hesitation.

Secondly, most of the participants approached the liquid as described in category D,

with attempts to associate it to the microscopic models (either ball and stick models they had made that were in front of them or they employed the knowledge of the models related to the particle nature of matter in D2) or symbolic representations such as structures (in D1).

Thirdly, the liquid in a bottle was associated with the laboratory classes (category C). The students' descriptions in which they made links between the liquid in a bottle and laboratory classes indirectly disclosed how students see the role of laboratory classes in teaching and learning chemistry. The three insights are described below.

(a) The Power of the Liquid Appearance

When confronted with a 'real' colourless liquid of 2-butanol and asked to relate it to the ways they described visualisation of a molecule of 2-butanol, two sorts of participants' responses were distinguished, the emotional one and the verbal or descriptive one. Although emotional responses contributed to the students' verbal responses, their significance on student conceptualisation was not analysed by the descriptive analysis and the findings in a form of the categories of description. The power of the appearance of a liquid in a bottle initiated students to think about what would be the suitable answer in their world of chemistry to respond to the 'real' liquid. The diversity of students' responses, in which many students had tried to drag down everything from their knowledge of chemistry to explain what was observed, was a surprise. The power of a liquid being shown, which was the world students were able to see, was mirrored in their description.

To Ben, whose quotes were placed in two categories C and D1, an appearance of 'runny' liquid initiated a handful of diverse thoughts, from association to the short chain (symbolic) to those within the visible world (water, laboratory classes). Others also recalled water, a familiar liquid to them, and chemistry laboratories as places where they experienced liquids in chemistry.

While five participants admitted not being able to picture the molecules floating around, the liquid in the bottle initiated a number of students (category D2) to associate the movement they were aware of from their mainly abstract knowledge of chemistry and the visible moving of the liquid when bottle was shaken. For example Erica described how she "... can picture these little things floating around and stuff." Romy and Steve imagined tiny 'representations' floating around in the liquid. Faced with the 'real' liquid

Rudy found the word 2-butanol floating around (a name or label from the world of chemistry they have been introduced into).

(b) Description of Liquid Based at the Molecular Level

The history of chemistry suggests that, starting from the macroscopic description only, chemistry evolved into a science discipline, in which the symbolic interpretations started to be used for an explanation of chemistry phenomena (Johnstone, 1993). During the last twenty years the growing awareness of the importance of understanding chemistry at the microscopic (molecular) level contributed to the on-going development of chemistry as a science discipline. Johnstone highlighted how an understanding at the microscopic level is crucial in understanding of complex scientific phenomena in chemistry today.

A number of studies have shown that an understanding of the particle nature of matter is important in understanding chemistry and a lack of understanding of the scientific phenomena in chemistry was often linked to a lack of understanding of the phenomena at the molecular level (Gabel, 1993; Gabel, 1999; Lee et al., 1993; Krajcik, 1991; Stavy, 1995). Lee et al. (1993) investigated students' conceptions concerning the nature of matter and the arrangement and motion of molecules at the molecular level as well as their macroscopic conceptions concerning the nature of matter and physical changes. The authors added that apart from the importance of the particle nature of matter, a scientific understanding of much chemistry, including the observable aspects of phenomena, requires from students an understanding of kinetic molecular theory. Studies by Gabel (1993) and Gabel et al. (1987) explored student understanding of the particle nature of matter or student conceptions at the molecular level compared to those at a macroscopic level.

The educational research that reported the importance of the particle nature of matter and the kinetic molecular theory in understanding chemistry was mirrored in teaching chemistry. The ways in which most chemistry is introduced to the students today differ from the ways used in the past. Because understanding of the particle nature of matter has been identified as important in understanding of chemistry, teaching chemistry today is mostly based upon the use of different micro models. Textbooks are full of the representations at the molecular level, similar diagrams or models are used at lectures. Additionally, in a technology enhanced teaching environment, many chemistry teachers

and educators found the use of computers useful for demonstrating various microscopic representations and simulations.

The research of the authors mentioned above suggests moderate reflections of such teaching. The present study demonstrates that 52 % of the students employed the concepts of the particle nature of matter and the kinetic molecular theory, both found in the categories D2 and E. In the subcategory D2 students associated and discussed a colourless liquid through the concept of the particle model (e.g. ball and stick model they had built during the interview) but also discussed the gas-liquid-solid particle distribution.

The participants' discourse in this study (subcategory D2) suggests that these students are conscious of the importance of understanding the microscopic level. Likewise, this discourse might be used as an indication that the participants' conceptualisation, identified in subcategory D2, was based upon the concepts of the particle nature of matter and the kinetic molecular theory, that have been emphasised in teaching. This strategy was employed by more than half of the participants. These results are in agreement with a discussion found in the phenomenographic study of chemistry students' conceptions of solubility by Ebenezer and Erickson (1996), in which the authors discussed how students tried to extend the macroscopic properties to the microscopic level and reported, "Perhaps one of the most powerful influences on students' reasoning in this domain is their tendency to use a strategy of extending the properties and behaviour of substances at the macroscopic level to explain phenomena at the microscopic level" (p. 196).

While the association at the molecular level was present in all the descriptions of the subcategory D2, not all the descriptions involved the kinetic molecular theory (discussion of the attraction forces and the constant motion of the particles). The results obtained within this subcategory differed from static to dynamic descriptions. A range of identified conceptions can be justified by the assumption that the participants in this study might have differed in the ways they conceptualised states of matter, an explanation which can be linked to the findings by Renström et al. (1990). Only the students who had developed a conception of matter as a system of particles with interactions between particles (Renström et al., 1990) were able to associate liquid to the dynamic model of the moving particles.

(c) *Links to the Laboratory Classes*

The ‘real’, colourless liquid in a bottle initiated some of the participants to recall laboratory classes as the places in which they experienced liquids in chemistry and the other aspects of real chemistry (Category C). Although it was not planned to be a target for investigation in this study, this connection to laboratory classes revealed the ways in which the participants in this study experienced the laboratory classes.

Laboratory classes are part of the regular chemistry course. Solomon (1988) described that most practising science teachers “think that experimental has a key role to play in this teaching because it so clearly illustrates and brings to life the ideas that would otherwise be confined to words on paper” and that they know that “practical work is popular” with many students (p. 104).

Indeed, the responses in which students associated the bottle of colourless liquid labelled 2-butanol to the tests in the practical laboratory classes (Category C) could be used to support the enthusiasm of the science teachers. Carl was one of the participants who made the connection between the ‘real’ liquid of 2-butanol and his laboratory classes. He suggested that he is “used in the laboratory to having liquids and other chemicals reacting.” He later also recalled the reactions of alcohols he had done during the laboratory class. However, according to Solomon, providing all the experimental back-up still does not guarantee learning because the ‘hands-on’ experimental has two stages. In the first stage the participants “follow the suggestions given and obtain, with great pleasure the expected result” (p. 107), but do not achieve understanding. The understanding is achieved in the second stage, in which the students are able to explain and demonstrate that they have mastered both the concepts and the equipment manipulation or procedure. According to Solomon, the second stage is rare and “just occasionally, if there is sufficient time, a rarer stage is achieved” (p. 107).

The ways in which the participants of this study talked about laboratory classes suggest that their experiences of laboratory classes might have reached the first stage, but not the second one. Ben’s quote in which he described the way he experienced laboratory classes, “Do a bit of chem lab, adding to this, it changes colour and end up with a few calculations”, suggests that, although at undergraduate level, this student has only achieved the first stage.

Hodson (1993) talked about practical work in doing science in a sense of conducting

own investigation in which students refine their conceptual or scientific knowledge and develop their procedural skills or knowledge, which does not necessarily have to involve bench work, but can be performed using alternatives such as CAI. Tasker (1981) identified several reasons for students' unsatisfactory learning in laboratories. The first pointed out that lessons are perceived by students as isolated events, not as part of a related series of experiments. The second highlighted that a student's purpose of laboratory work "following the set of instructions or getting the right answer as a purpose for a scientific task" (quoted in Hodson, 1993, p. 102) differs from the one of a teacher. Hodson (1993, pp. 101-102), who reviewed the rationale employed in the promotion of practical work and the ways in which this has changed over time, discussed:

.. conceptual understanding requires us to go beyond the concrete: 'ultimately, the relevant concept has to exist as an abstract concept if it is to be fully operational'. Although students in laboratory classes spend a great deal of time handling real materials (magnesium and sulphur, magnets and iron fillings, geraniums and gerbils), they are required to discuss and interpret their findings and to provide explanations of observed behaviour in terms of abstract concepts (electrons, chemical bonds, magnetic fields, photosynthesis, and the like). In most contemporary curricula, it is familiarity with the underlying abstract concepts that constitutes the real learning goal.

So, although students perceive the laboratory as a place where they are active (in sense of 'doing something'), many fail to see the connection between what they are doing and what they are learning (both in terms of conceptual knowledge and procedural knowledge).

The insights obtained in this study suggest that laboratory classes are experienced more as separate and not as integrated parts of the course, and are in agreement with a discussion by Hodson (1993) given above.

Johnstone (1997) also pointed out that much has been published about the wonders of laboratories, but not enough about nonlearning in the laboratory situation. Although Johnstone (1999) asserted that the practical time in a laboratory should bring the macro, micro and symbolic (representational) aspects of chemistry together, this is precluded because students are faced with a number of things to do in any laboratory experiment; a number of instructions to be followed, a number of important observations to be made, and a number of theoretical ideas to be recalled to make sense of observations and instructions (Johnstone, 1997). Johnstone talked about information overload, as most laboratory classes consist of 'an avalanche of things to do and little time is left for

thought' ("you only have to ask students in a laboratory what they are doing to be told which page and line they are at and not what shafts of intellectual light are dawning"). Information overload causes overloading of the student's working memory and Johnstone talked about preparation time needed to provide the students with the requisite theory and help them in establishing the equilibrium between the long term memory and the working memory during the learning process. Similarly, Draper (1998) described the instructional design as a crucial pedagogical weakness in many laboratory classes. According to Draper, in a laboratory, students are usually occupied by the mechanical procedures and follow a fixed set of steps in order to get the official results and are not intellectually engaged with the conceptual issues.

The discussions given by Johnstone and Draper are in agreement with Solomon's (1988) comments that only the first stage of learning by experiments could be achieved, but not the stage in which the understanding is achieved.

The students' comments in this study are in agreement with those reported in the literature. Additional support for these findings was found in the students' descriptions in Study One. Terry's quote (used earlier in Chapter 6 as support for her individual preference for the computer-based tutorial over a hands-on experiment), reveals that the way she experiences laboratory experiments agrees with the discussion reported in the literature (by Johnstone, Draper and Solomon):

I think you learn more with the computer because, like, if you just run the practical part you don't have to think about it, you just do it ... coming to the computer part should help restructure what you've just done and it's good because it shows in a basic form .. I think the computer program is very important 'cause it helps you to reinforce ideas you should be thinking about doing the experiment. .. Otherwise you do the experiment and keep go thinking.. oh, let's get as fast as you can, and don't think about it as when you come here, you have to sit down and think about it, which is good. (Terry)

According to Johnstone (1997), a form of prelabs, for example, can be used for preparing students' minds for expected changes, and providing students with the requisite theory appeared necessary for processing the laboratory experiences with understanding. Prelab face-to face and in some cases preparations on computer are offered to Chemistry 101 students at Massey University.

(d) New Insight from the Study: Dream World - Real World

The power of the appearance of a liquid that initiated very diverse student responses

brought about the new insight described below.

The point in the interviews where the students were confronted with a liquid of 2-butanol provided insights into the way the learner copes with learning chemistry. In the previous section these insights have been fitted into the framework of the symbolic, microscopic and macroscopic triangle of chemistry (Johnstone, 1991). An additional insight, which complements the concept of the three-fold nature of chemistry, emerged from repeated reading of the transcripts. It arose from the comments made by some of the students with the most complete understanding of the concepts explored, when confronted with an area of uncertainty. No attempt or thought was given to reasoning through the problem. Instead students' comments such as "I haven't studied it" etc. (as discussed before) revealed that the visualisation of molecules was considered to be an ability which students can only have after having been taught it.

Also, the first emotional responses to the sight of colourless liquid suggested that 2-butanol in a bottle was experienced in a way which differs from any other experiences described by the students during the interviews. Hodson (1993, p. 109) described:

However, we should recognise that a student's personal understanding comprises not only a complex network of denotative and connotative meanings, but also an array of feelings and emotions that are instrumental in determining learning.

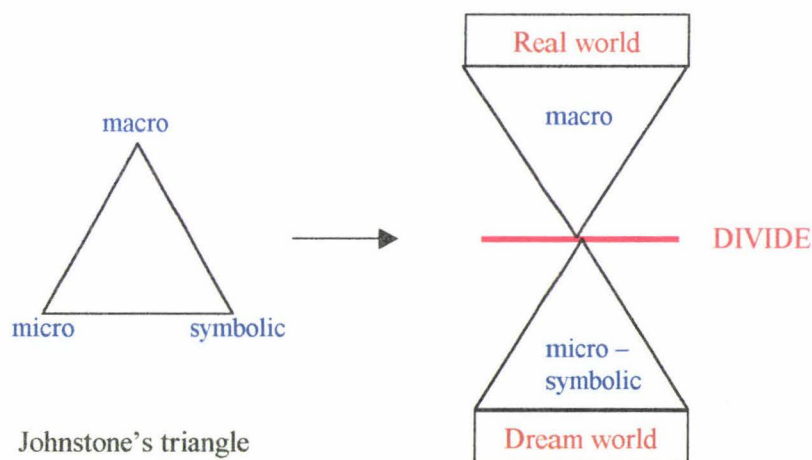
The reaction from the students (verbal and emotional) to the colourless liquid revealed their realisation that the world of chemistry they were being taught was a different 'dream world' separated from their real world. Here, 'dream world' is taken to mean a body of knowledge which must be taught and involves a construct with the purpose of providing a framework to understand the 'real world' that is all around. The term is coined with an awareness of the dream time of the Australian Aborigine which also is taught to provide explanations for the real world, which deepen the learner's understanding.

In this study this phenomenon is named the 'dream world' – 'real world' concept. This new concept makes a distinction between the world of chemistry, called 'dream world' that involves micro-symbolic dimensions or corners of Johnstone's triangle (which are both mind constructs) and the real world of chemistry (the macro dimension from Johnstone's triangle). It differs from the Johnstone's triangle which treated equally the three aspects of chemistry. According to the 'dream world'-'real world' concept, both

his concepts of micro and symbolic lie squarely in the dream world and are not treated in a same way as the very different real macro world.

The principles of the ‘dream world’ – ‘real world’ could be easily demonstrated using an example of water. Whether we take a symbolic representation of water as H_2O and relate it to a glass of colourless liquid or a micro representation based on quantum calculations, e.g. , and relate it to a glass of water, we are always working on the boundaries between the two worlds.

The diagram shown in Figure 8.2. suggests a change in the concept of understanding chemistry based on the results of this study, from Johnstone’s micro-symbolic-macro concept of equally treated dimensions of chemistry to the ‘dream world’-‘real world’ concept in which the two worlds are separated from each other.



Pavlinic, 1998

Figure 8.2. A change in concept of understanding chemistry based on the results of Study Three, from Johnstone’s (1991) micro-symbolic-macro concept of equally treated dimensions of chemistry to the ‘dream world’-‘real world’ concept in which the two worlds are separated from each other.

The “dream world – real world” concept differs from Johnstone’s triangle. Johnstone’s triangle is a chemist’s (and lecturer’s) framework used to explain difficulties in learning chemistry. It is used as a guideline in teaching with an aim to facilitate the learning of chemistry. It has also been used as a framework for the research undertaken in this study. It assumes an integration of microscopic, symbolic and macroscopic aspects, but Johnstone himself acknowledged that students had difficulties in linking aspects of the triangle and that the integration may be achieved only after many years spent dealing

with chemistry.

The “dream world – real world” concept is a student’s framework, based on the ways he/she experiences chemistry. It evolved from the background having the assumptions of Johnstone’s triangle, but proved to be different.

The macroscopic dimension (real world) is not treated equally as the other two dimensions, symbolic and microscopic (dream world). The “dream world – real world” concept highlights the problems learners cope with every time they try to link the two worlds together. The ways such links are made is not predictable and a teacher’s simple explanations given to solve the problem may not suffice. The ‘dream world’ of the chemist is complex, sophisticated and powerful but from the responses of the students facing a real liquid, it is also clear that it is an artificial construct made up by elders, which the students must learn.

While both models contribute to our understanding of the ways we learn chemistry, the positions of the two models are different; theoretical versus as it is, so the “dream world – real world” concept distinction adds a new insight to our understanding of the ways we all learn chemistry.

With this insight the diversity of the students’ responses to the liquid becomes understandable. Firstly, that real liquids, solids, gases do not normally enter the ‘dream world’ but exist in places like laboratories. Secondly, the part of the information in the ‘dream world’ that is selected by a student to describe the liquid 2-butanol, is to some degree arbitrary (perhaps sometimes the only thing that is remembered or the first thing that comes to mind), particularly for those who are less competent. The trained chemist is more competent to work at the boundary between the two worlds, as he/she may be more adept at identifying the key feature of interest.

If viewed within the frame of the ‘dream world – real world’ concept, the students’ description of the ways they experience laboratory classes separated from the rest of the course become understandable.

The ‘dream world – real world’ concept has the power to shake trained chemists out of the comfortable belief that teaching factual information would make a chemical idea immediately obvious to the thoughtful student. If recognised by the chemistry community and in teaching chemistry, then we all might have different expectations of both the teaching and the learning of chemistry.

Although Johnstone's model is a powerful way of viewing the problem of teaching chemistry, the results of this study show that it may also prove deceptive for the teacher in understanding the position of the learner. In this study the variety and intensity of the responses of the students to being confronted with a real liquid suggest that the significant divide is between real materials that can be touched, seen and smelled and the mental construct the teacher is so carefully presenting in class. Johnstone's triangle gives the microscopic, symbolic and macroscopic dimensions equal weight, whereas the model proposed here collapses the symbolic and the microscopic back into the elegant dream world developed by generations of chemists and keeps the attention of the teacher, and through his/her awareness, the students also, on the most significant process that is taking place as they learn chemistry, which is in understanding the world of chemistry in relation to the real world around us.

With the focus restored to this most significant boundary both teacher and student can confidently advance into all aspects of the dream world, whether microscopic, macroscopic, spectroscopic, thermodynamic or any other kind.

(e) *Problems in Linking the Macroscopic Nature of the Substance to Student Visualisation / Predicting Properties of a 'Real' Liquid*

In the quotes that were assigned to higher categories (D, E) the students used the information from their knowledge of chemistry to explain a property of a 'real' substance. For example, in D1 sub-category, the symbolic description was readily employed to address the liquid state of a matter by Ben who associated: "fluid because it is a short chain", or Kay: "it's a liquid, it's an alcohol" or Tammy who explained "how it is to react is to do with its formulae." The other examples were when the participants tried to explain the liquid state by recalling the microscopic particle distribution or when they tried to explain the moving seen in a liquid by the interactive forces between the particles (D2 and category E).

However, for many students this was not seen as an easy task. For example, Carl asked the fair question: "How am I meant to tell it's a liquid if I have never seen 2-butanol before?" In desperation Carl talked about writing down four Carbons – "it is actually faster to write it down" and indicated how difficult it could be to use the information from the body of chemistry knowledge he was taught ('dream world') to understand the properties of a substance ('real world').

Students had been taught chemistry in abstract terms. Ken described how “visualising molecules is sort of only theoretical” and how “at school we spent more time doing this with theoretical models, rather than actual experiments “. But, can the real world tell us anything about the abstract nature of chemistry or inform students about their dream world? Looking at the ‘real’ liquid in a bottle Eddy concludes there is “No way of telling what the atoms look like this just by looking at a bottle of 2-butanol”.

In conclusion, not only has the gap between the dream world and the real world been clearly identified, but the students also indicated the reasons for the gap. They talked about the problems of looking at the real liquid and visualising and thinking at the molecular level (see Eddy’s quote in the paragraph above). Jody admitted having “quite a lot trouble going from ball and stick model or skeletal formula to something physical, like the liquid”, or Thai “Wouldn’t you just say it’s 2-butanol in the bottle. I would never think at the molecular level”.

Some of the participants felt comfortable with the world that exists (real world) and associated their difficulties in learning chemistry to the dream world, such as Ben: “Probably why I have so much trouble in chemistry - I don’t really know whether atoms really exist”. On the other hand, Jody explained being confident with the dream world but finding difficulties in linking it with the real world: “That’s the same problem in the lab as well as, you know it’s all going well on the paper, but when you actually see it it’s quite difficult”. Regardless of the starting point, once the two worlds are met, the student responses indicated the presence of the dream world – real world gap.

In trying to link the real world with their visualisation the participants emphasised the role of the ways they were taught chemistry. Ken talked about “doing more theoretical molecules rather than the experiments”, while Carl’s explanation of how he had “..never seen 2-butanol before and you try and teach me on paper ..” sounded like an apology for not being able to provide an appropriate explanation.

The students’ responses indicated that the problems in linking the real world with the student’s dream world are of a multiple nature, one of which is related to the characteristics of the individual student, another to the way chemistry is introduced to students. The nature of the chemistry instruction was investigated and discussed in the literature by Gabel (1999) and Johnstone (1991; 1997; 2000). The ways the students constructed their dream worlds of chemistry are influenced by the ways chemistry was taught to them. This additional analysis is in agreement with earlier discussion which

argued that the students' visualisation depended on the ways they were taught chemistry (see section 8.3.2. (iv) Discussion). Support for such a claim is found in the literature (Laws, 1996; Ramsden, 1993; Shepard & Gilbert, 1991), in which the authors suggest that students' science conceptions and their learning approaches are influenced by the ways in which knowledge is structured and presented to them.

The Role of Experience and the Time Spent in Learning Chemistry

Since 1991, when the threefold nature of chemistry was introduced by Johnstone, Johnstone pointed out that it takes a long time to grow familiar with new concepts, but also indicated that once the new concepts are embedded in a long term memory they can be used as a powerful way of looking at the world (see Information processing theory in Chapter 2). This is in agreement with Lemke's view (1994, 2002) that the integration of different abstract concepts in science happens spontaneously only in a later stage of learning and after many years of experience. The same can be applied to the 'dream world – real world' concept, in which the experience makes a trained chemist more competent to work at the boundary between the two worlds. However, an experienced expert might help students by showing them how he/she works, which is in agreement with Vygotsky's sociocultural view.

(iv) Conclusions

The findings, in which students related a macroscopic sample of the substance to their visualisation of molecules, were given in a form of hierarchically ordered categories of description.

It was suggested that the students' discourse mostly mirrored the ways they were taught chemistry both at high school and at university. For example, the chemistry instruction given to the students at university was supported by the use of physical ball and stick models, space filling models but also the use of dynamic computer generated microscopic representations, based upon the kinetic molecular theory; also in the prevalent category D2, the students responded to the sight of a liquid by recalling the dynamic micro models in which the properties of a liquid were explained by applying the understanding of particle nature of matter and the kinetic molecular theory.

Therefore, this study revealed that students today make use of more micro models in their descriptions as these have been more emphasised in the teaching of chemistry. For

example, the literature advocates the importance of the use of particle nature of matter and the kinetic theory in chemistry instruction to achieve student understanding of chemistry (Gabel, 1993; Gabel et al., 1987; Lee et al., 1993).

However, a recent article by Tsaparlis (2001a) suggests that the way chemistry is taught to students, which applies the molecular-atomic-electronic nature of chemistry, is the most important factor generating learning difficulties and that teaching and learning about atoms and molecules are heavy tasks for both teachers and pupils:

Despite the calls from science-education researchers, chemistry textbooks continue the practice of treating too much abstract material at an elementary physical chemistry level. (p. 64)

In trying to provide an adequate response some students stayed within the observable or macro nature of a chemical compound associating the colourless liquid either to water or to substances they have seen in laboratory classes (category C). The insights from the responses in which students talked about laboratory classes are important as they provided evidence that the students' experience of laboratory classes does not necessarily agree with the intentions (learning objectives) of teachers/course developers of what the laboratory classes should provide to the students (gaining both practical skill and conceptual understanding).

The diversity and richness of the students' responses when being confronted with a liquid brought an additional insight, called in this study, the 'dream world – real world' concept. The new concept suggests that the gap between chemistry of the real substances and the abstract body of chemistry knowledge is wider than usually recognised and discussed in the literature. Tribute must go to Johnstone (1991; 1993; 1999; 2000) for his contribution and the others who articulated his ideas (Gabel 1999). However, a division between the two worlds of chemistry, such as observed in this study, has not been sufficiently elaborated by the wider chemistry community.

Although a recognition of the difference between the microscopic and symbolic aspects of the body of chemistry knowledge is useful, the findings of this study suggest that the most significant distraction for the student learning of chemistry seems to be between the world of real substances (the macro world according to Johnstone) and the body of abstract knowledge the students are being taught (the micro and symbolic worlds of Johnstone).

The ways in which the participants in this study described their experiences of

chemistry suggest that the thinking and understanding of chemistry across the micro-symbolic-macro nature of this science discipline either does not exist or is at best remote from the closeness assumed by professional chemists or educators, at least for the first year undergraduates who participated in the study.

In conclusion, the teaching of chemistry should attempt to take into account the dream world - real world divide and take every opportunity in attempting to bridge it either during the introduction of new concepts or after the concepts have been mastered and need to be applied in a real world situation. An attempt to bridge the dream world - real world gap of stereochemistry in the tutorial was the aim of the study that follows.

8.5. CONCEPTUALISATION OF DIFFERENT ISOMER TYPES

The computer-based stereochemistry tutorial that was described in Study Two addressed different types of isomers: structural isomers (also called constitutional isomers) and stereoisomers (conformational isomers and configurational isomers - enantiomers and diastereomers (*cis-trans* isomers)). In order to analyse all types of isomerism that are addressed in the tutorial and to answer the Research Question 3c:

In what ways students conceptualise each isomer type?

student conceptions of these different types of isomerism were collected during the interviews. To explore the concepts of some stereoisomer types, the researcher generated supplementary sheets that had drawn structures showing the stereoisomeric relationships between them.

The results reflect the ways students conceptualised different isomer types and were revealed either from the description given during the interviews or from the responses on the structural representations of different isomer types in supplementary sheets shown to the participants during the interviews (see Appendix 5 for an example of interview transcripts and supplementary sheets).

8.5.1. Analysis of Students' Responses to Each Isomer Type

Structural isomers - The participants used words, drawings and physical models to describe the ways in which they visualise molecules. Having made drawings or a

physical ball and stick model to illustrate the ways in which they visualise a molecule of 2-butanol, students were asked: “Is it possible to rearrange these atoms in some other order?” or “Is this the only way you can arrange these atoms together?” The questions aimed to reveal the students’ conceptualisation of structural isomers.

Conformational isomers - When the students rotated carbon-carbon bonds while playing with the ball and stick model, insights into students’ thinking about conformational isomers were gained. Apart from that, the insights about conformational isomers were collected from the students’ responses to the researcher generated supplementary sheet (the sheet is given together with the results) that was presented to the students during the interviews.

Enantiomers, Diastereomers - For these isomer types (stereoisomers), insights were collected from the students’ responses to the researcher generated supplementary sheets that were presented to the students during the interviews (the appropriate supplementary sheet is given together with the results for each isomer type). These supplementary sheets contained structural representations, commonly found in most chemistry textbooks and were designed to probe the students’ understanding of different stereoisomers of organic compounds. When shown the sheet showing the structure/s, the students were asked: “How would you describe this structure?” and/or “How would you describe how these structures relate to each other?”

Step 1- Individual responses

In the first step, analysis was carried out for each individual participant as an extension of and in conjunction with the analysis that preceded the analysis described earlier for visualising molecules (phenomenon one, see Tables 8.4, 8.5. and 8.6.). The participant was shown a sheet and asked to describe either the structure shown or the differences between the two structures. The responses to the supplementary sheets that contained diagrams of different isomers were used to give an indication of how an individual participant might understand different types of isomerism.

Table 8.15. gives an example of the analysis which considered individual participant responses in conjunction with the analysis of individual visualisation. The data for all participants are given in a table (Appendix 5, (c) Analysis process - Step 4).

Table 8. 15. The initial step of the analysis of student awareness of isomerism.

Particip./ Trans. no.	Initial visualis.	Descr. ability	Shape		Type of Isomerism				Term
			Aware	Descr.	Struct.	Stereoisomers			
						Confor.	Configurat.		
							Enan.	Dias.	
Paul (2)	2D -> SF	**	**	**	**	**	**	*	**
Ben (3)	2D	*#	#*	#*	**	#*	*#	*#	#*
Andy (7)	3D wedges	**	**	**	**	*#	**	*#	**
Jack (24)	2D / B&S attempts, incomplete	*#	#	#	*#	#	#*	#	#
Mark (25)	3D sophis.	**	*	*#	**	#*	**	**	*#
-----	-----	-----	-----	-----	-----	----	-----	----	----
Rudy (1)	3D sophis.	**	**	**	#*	#*	**	*	*
Tammy (4)	2D shaped	*	*	#*	**	##	##	*#	#*
Cara (12)	2D	*#	#*		#*	#	*	*	#*
Meg (22)	2D linear, incomplete	#	#	#	#	#	#	#*	#

Descriptive ability legend

- ** clear and meaningful sentences, use of scientific language and own words (understanding)
- * try to explain the meanings by repetition of scientific definition, laws (formal knowledge)
- *# show understanding but unable to describe it on their own (lack of words)
- #* partial ability to recall scientific meaning, often contradictory statements
- ## poor descriptive ability, lack of formal knowledge but also inability to use own words to describe phenomena

Shape legend

- ** able to recognise and describe it, use of scientific terms and own words, atom sizes awareness
- * familiar with, recognise and describe common shapes
- *# able to name and describe some shapes when reminded, not sure
- #* partial ability to recall some names when reminded, but do not show understanding
- ## not familiar, not able to recall the meaning even if reminded

Isomers legend

- ** very familiar, able to recognise and describe it, use of scientific terms and own words
- * partial awareness, familiar with types introduced at high school
- *# familiar when reminded, not sure
- #* aware of some properties, not able to assign it to isomers, heard about when reminded
- ## not aware of properties, not familiar at all, even if reminded

Step 2 – A range of meanings for each isomer type

In the second step of the analysis, the responses from all the participants were integrated. The quotes from different participants were grouped together according to different types of isomerism which allowed the researcher to analyse the students' conceptualisation of different isomeric possibilities of organic compounds. The grouped

quotes were named according to the types of isomerism: structural isomers, conformational isomers, enantiomers and *cis-trans* isomers.

In assigning the ways of conceptualising different isomer types, the following criteria were considered:

- Student familiarity with a particular type of isomerism,
- Student ability to recognise the isomer type,
- Student ability to name the isomer type using chemical terms,
- Student ability to describe the isomer type in terms of properties relevant to the certain type of isomerism.

Step 3- Categories of description for each isomer type

For each isomer type, the quotes with different meanings formed the ‘pool of meanings’ and were phenomenographically classified into the categories of description. The procedure that involved differentiation of students’ quotes according to the similarities and differences between the meanings embodied in the quotes that resulted in the categories of description for each isomer type was the same as described earlier.

The phenomenographical approach was employed for each isomer type and the details of steps 2 and 3 are given prior to the results for each isomer type separately. Most interviews were held in March 1999 (twenty one in the period 03/03/99 – 01/04/99, with four at the end of the semester from 28/05/99 - 31/05/99). Due to the variable student exposure to lecture material that influenced the participant’s extent of understanding of different isomer types, no attempt was made to express the distribution of the categories across the participants in percentages.

8.5.2. Students Describing Each Isomer Type - Results

(i) Structural Isomers

When asked “Is it possible to rearrange these atoms in some other order?” all of the participants responded positively to the challenge to rearrange atoms in some other order. Most of the students (21 out of 25) described how they were familiar with the term structural isomers from high school. Table 8.16 shows the distribution of the responses for structural isomers, identified from the individual participant’s description.

Table 8.16. Students' awareness of structural isomers distributed to different means of responding.

Student Pseudonym / No. of transcript	Awareness of structural isomers				
	Not aware	Same type of compound	Different arrangement	Properties	More complex awareness
Paul (2)		✓		Mentioned	
Ben (3)			✓		
Andy (7)			✓		
Dan (8)					✓
Steve (9)			✓		
Eddy (10)			✓		✓
Lee (11)			✓		
Ken (16)			✓		✓
Carl (18)			✓		
Martin (19)		✓	✓		
Dug (23)		✓			
Jack (24)		✓		Mentioned	
Mark (25)					✓
Rudy (1)				✓	✓
Tammy (4)			✓		✓
Erica (5)		✓	✓		
Romy (6)				✓	✓
Cara (12)		✓			
Thai (13)			✓	✓	✓
Caly (14)	✓	✓		should have diff. prop.	
Marry (15)		✓			
Amy (17)	✓				
Jody (20)	✓				
Kay (21)		✓	✓		
Meg (22)	✓				
No. of student responses / total	4	9	12	6	8

Pavlinic, 1999

(a) Categories of Description

Further analysis resulted in four different categories of description in which students

described structural isomers, shown in Table 8.17.

Table 8.17. Categories of description for structural isomers.

Category/Referential aspect	Structural aspect
A – <i>Not aware</i>	No understanding was shown. Participants did not mention the isomerism on their own and responded negatively to the researcher’s question “Have you ever heard about structural isomers?”
B - <i>Structural isomers - the same type of organic compounds</i>	Focus on organic molecules with the same functional group; Limited understanding of the concept, but still unsatisfactory.
C - <i>Different arrangement - structural isomers</i>	Satisfactory understanding of the concept
D - <i>More complete conceptualisation</i>	Satisfactory understanding of the concept in which, apart from the change in structure, the students commented on different properties of structural isomers

Pavlinic, 1999

Category A – *Not aware*. Although responding positively to the possibility of rearranging atoms, the participants’ responses in this category did not show signs that an understanding of structural isomers was achieved. The participants did not mention isomerism on their own and responded negatively to the researcher’s question “Have you ever heard about structural isomers?”

Category B - *Structural isomers - the same type of organic compounds*. In this category the participants described that the only way of rearranging the atoms, would be the possibility of changing the position of OH-group from the second carbon to the first carbon. When asked about the relationship between the two structures, some described them as structural isomers on their own, some confirmed familiarity after being reminded of isomers:

Jack: Well, the only other way is .. put the OH group on the first carbon which is identical if we put it on the first carbon there, while is originally on the second carbon. If we put it on the third carbon it’s really just the second carbon again, they are the same, so there only two ways you can have it, the OH group on the first carbon or on the second carbon.
R: How do the two structures relate to each other?
Jack: Well, obvious, they are not exactly the same .. they really rearranged structurally in different ways, so I mean, structural isomers.

The students’ descriptions and therefore conceptualisation of structural isomers were

limited to the possibility of rearranging groups within the given organic compound, in this case, alcohols. When asked about the possibility of putting an oxygen between the two carbons, some of the participants agreed but added that it wouldn't then be an alcohol any more:

It would change the structure, wouldn't it? Would it be, you couldn't have it between, otherwise it wouldn't be an alcohol. Um I wouldn't have thought so.
(Erica)

The episode below indicates how Jack assumed that structural isomers have the same number of atoms with no change in the bond order:

Jack: .. which of course means none of the actual atoms have changed, they are still same number of atoms and the .. for that matter the same bonds, you don't have the double bond appearing somewhere.

R: What about an arrangement with a double bond as well?

Jack: You have to lose another hydrogen which wouldn't be the same number of atoms, so would be different, you know, wouldn't be the structural isomer of 2-butanol.

As the interview continued, Jack explained that structural isomers represent:

.. same compound, well, I mean in a way, yes but I mean when you move parts of it, if it's structurally different it's not just going to react the same as um, as it originally was. I mean for instance this one, it's not going to react the same way with the um, OH group on the first carbon as it is with the second so it will react differently. It's not exactly the same in that respect.

Category C - Different arrangement - structural isomers. In this category the meaning embodied in the students' description clearly demonstrated the relationship between atom arrangement and structural isomers. When asked: "Is it possible to rearrange these atoms here in some other order?" a number of students' (ten of twenty five) first responses were questions like "Do structural isomers, is that what you mean? (Martin) or "What? A structural isomer?" (Carl). These responses indicated how students associated the term "different arrangement" directly with the term structural isomers. The interview episode given below illustrates the same point:

R: Is it possible to put the oxygen atom somewhere inside the chain?

Steve: Yeah, you could, it would be an ether.

R: What is common between these three different structures? [the two structures discussed earlier have -OH group on the first carbon and on the second carbon respectively]

Steve: They are all structural isomers.

R: When you are saying structural isomers

Steve: They got the same atoms but arranged differently.

Some of the responses from the students who initially believed that structural isomers have the same type of functional groups until being asked “Is it possible to put an oxygen between the two carbons?” were added to this category. The question suggested to them other isomeric possibilities that they had not recalled at first.

Category D - *More complete awareness.* In this category, students’ descriptions were more elaborated, in which they clearly explained that structural isomers assume a wide range of different types of chemical compounds:

Well, you couldn’t grab this and decide to have a ketone suddenly without doing anything to it. It’s just on the paper. If you see C_4OH_{10} there is no way that you could say that is 2-butanol, it could be 1-butanol, and could be like this, carbon here, um, this could be three carbon chain with a methyl group of here and um, double bond O, whatever, you don’t know, it’s a plenty different things, you just have atoms on the paper represented by empirical formula, they actually, .. with this you know that it is in fact alcohol but you still don’t know if it’s primary or tertiary or secondary. (Dan)

.. Um Ok it’s Um, it’s using all the same number of hydrogens and carbons and the one oxygen, but they are just rearranged differently in the molecule. It could be, like you could have a cyclic one and that would be a different isomer like um cyclobutane, cyclobutanol or something like that with an alcohol coming off. It just means that they have all the same molecular formula but rearranged differently. You could move them around, I guess, but it’s going to be a different isomer of that. (Tammy)

Also, some of the responses assigned to the group *More complex awareness*, included students explaining that different structural isomers have different properties, chemical (e.g. reactivity) or physical (e.g. melting point):

Structural isomers. Um, they have all the same atoms, they’ve changed their position in the bonds where the atoms are joined to each other, changed their positions in a different molecule, different properties, not the same .. (Paul)

Um it’s different, it’s going to have the same molecular formulae, Um but it’s a different isomer so it would probably react differently. [she is talking about having an oxygen between the two carbons and not as an OH group any more] (Thai)

There is structural isomer which is when we get the different structure like this one here, but there are also, I think it is a chemical isomer because this one here is a different where this one is an alcohol this is a carbonyl, carbon atom, but it’s um, it’s got different chemical properties like different melting points, because oxygen is connected to two carbons it is going to be less polar than the one we had before, so, probably will have lower melting point, boiling point, melting point ... , so it has some different chemical properties, probably would

have different colour as well. (Caly)

(b) Category Distribution Across the Participants

The quotes from the individual participants in some cases contributed to more than one category (see also Table 8.16. given earlier in the analysis process)

For example, nine responses from nine different participants described that the only way of rearranging the atoms would be the possibility of changing the position of OH-group from the second carbon to the first carbon.

However, some students believed that structural isomers have the same type of functional groups until being asked “Is it possible to put the oxygen between the two carbons?”. The question suggested to them other isomeric possibilities that they had not recalled at first. Out of the nine participants who initially thought about structural isomers retaining the same functional group, four responded positively to the question asked. Their responses were added to the next group of responses (see Table 8.16. given earlier in the description of the analysis). However, the analysis revealed that only two participants moved to the next category C.

Table 8.18. shows the category distribution for the concept of structural isomers per participants.

Table 8.18. The category distribution for the concept of structural isomers across the participants.

Category	No. of Participants
A	3
B	7
C	7
D	8

Pavlinic, 1999

In conclusion, four categories of description with increasing conceptualisation of the concept of structural isomers were identified. The participants whose responses were classified in categories A and B demonstrated that they had not mastered the concept of structural isomers to a satisfactory level. Those responses were collected from 10 different participants, mainly due to the misconceptions that structural isomers, apart from the same kind and number of atoms, must retain the same functional groups

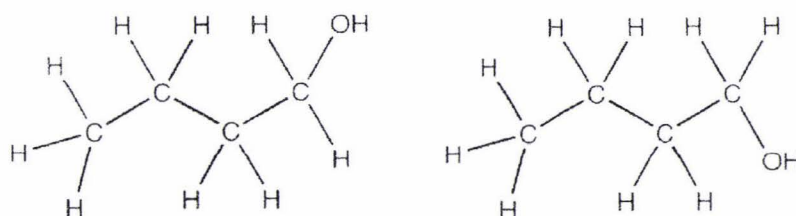
(category B). The findings for structural isomers are similar to those reported by Schmidt (1992).

The conceptualisation in which the participants mentioned or discussed properties, but still conceptualising that structural isomers belong to the same group of compounds and retain the same functional group, was not counted as an insight that brings the ways of conceptualising into a higher category.

(ii) Conformational Isomers

Several episodes during the interviews provided the students with an opportunity to indicate their awareness of conformational isomers and at the same time for the researcher to analyse the students' responses. Two of them were selected for this analysis. The first moment to get insights into student awareness of conformational isomers was when students freely rotated the stick (bond) between carbon-carbon bonded balls (atoms) in the ball and stick model they had made earlier.

The second moment was when the participants were shown a researcher-generated supplementary sheet with the structures of chemical compounds represented in a conformational relationship, as shown in Figure 8.3. and were asked to describe the relationship between the two structures (shapes) shown on the sheet.



Pavlinic, 1999

Figure 8.3. A copy of the supplementary sheet that was used to collect the participants' conceptions of conformational isomers.

Similar to the analysis of conceptualisation of structural isomers (Table 8.16.), the responses from all participants relating to the awareness of conformational isomers were distributed to the different means. Table 8.19. gives the results for the selected participants, while the complete table is available in Appendix 5, (c) Analysis process –

Step 5.

Table 8.19. Selected participants’ awareness of conformational isomers distributed to different means of responding.

Student pseudonym /No. of transcript	Awareness of conformational isomers					
	Not aware	Bond rotation - the same compound	Bond rotation - isomer	Used terms	Reminded- recognised	Reminded - recall lecture
Paul (2)			✓	✓		✓
Ben (3)		✓				
Andy (7)		✓			✓	
Jack (24)	✓	✓				
Mark (25)		✓				
-----	---	-----	-----	---	-----	-----
Rudy (1)		✓				
Tammy (4)		✓				
Cara (12)		✓				
Meg (22)		✓	✓			
No. of student responses / total	3	22	3	4	5	4

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(a) Categories of Description

The further analysis resulted in four different categories of description in which students conceptualised conformational isomers, as shown in Table 8.20.

Category A – Not aware. The responses in which the participants could not describe the relationship between the two structures (shapes) and the short negative responses to the question “Have you ever heard about conformational isomers?” describe the lowest Category A. No sign of understanding was shown.

Category B - The most common response was *Free bond rotation - The same structure*. The participants were aware of the rotation about a single (sigma) bond. They demonstrated it using the ball and stick models and they also recognised that the two structures shown on the sheet differed due to the possibility of rotation about single carbon-carbon bonds. Because of the possibility of free rotation and interconversion between the structures, students described them as the same structures.

Ooh, .. basically they are both the same because, they are different in this diagram here, the OH group is down in the bottom here while here is in the middle, but if I put an OH group [uses ball and stick model] ... do it directly

because it's easy, um, that one is like that and that one is like that, I suppose a bit of twisting on the bonds here and other than that it's not really different, really, it wouldn't allow the structural formulae to be any different and those two things fit quite happily into each other and it wouldn't allow to separate them out because they just sort of freely moving around. (Cara)

In this category, the free rotation around a single carbon-carbon bond was not assigned to any kind of isomerism. When playing with the ball and stick model she had made and considering the rotation of the carbon-carbon bonds Erica said: “Um, different structures of the same molecular formula. So you can, yeah, you wouldn't really get isomers of this, but yeah, you can just rotate it.”

Table 8.20. Categories of description for conformational isomers.

Category/Referential aspect	Structural aspect
A - <i>Not aware</i>	No sign of understanding was shown. Participants could not comment on any difference between the two structures shown and responded negatively to the researcher's question "Have you ever heard about conformational isomers?"
B - <i>Free bond rotation - The same structure</i>	The participants demonstrated understanding of the concept of the free carbon-carbon bond rotation. However, no link to the isomerism was demonstrated.
C - <i>Recognised isomers after being reminded.</i>	The participants demonstrated the understanding of the concept of the free carbon-carbon bond rotation and described the two structures as conformational isomers after being reminded by the question "Have you ever heard about conformational isomers?"
D – <i>More complete conceptualisation</i>	<i>Bond rotation - link to isomerism; Conformational isomers - recall from lecture; The only difference is conformation</i> – All these means of responding indicate a more complete conceptualisation of conformational isomers.

Pavlinic, 1999

Category C - involves responses in which students described that free rotation could not lead to isomerism, but later *Recognised isomers after being reminded*. Dan, for instance, at first described the structures not assigning any isomerism:

They are both butanol, primary alcohols and the structures are basically the same, they are actually the same molecule, not different isomers or anything like that, because this bond rotated, you can give around to end with this structure here or vice versa, so in fact they are the same molecule .. yeah. [laughs]

But, later during the interview, after being asked if he had ever heard of conformational isomers, he added with uncertainty:

Yeah, are they, they are the same molecule it's just the bond rotated, so, yeah, I suppose they are conformational isomers. [laughs]

Andy also started with description:

Andy: ... This one here is the same molecule, um, except of, the only difference is rotation around one two carbon bond, so that the CH₃OH at the end is rotated, now they are, the OH is in a different position relative to the rest of the molecule. I'd just say it's the same molecule..

R: So, it is possible to convert one bond into another.

Andy: Yeah, just rotation around that single bond there

but, when reminded Andy was more confident than was Dan:

Yeah, yeah, that would be a conformational isomer then. Yeah, yeah, and could represent that, how we call the diagram, represent with that diagram, you look down the carbon-carbon bond..

Category D – The responses that were assigned to this category demonstrated a more complete understanding of the concept of conformational isomers. The category includes the responses in which the concept of bond rotation was connected with the isomeric possibilities (*Bond rotation - link to isomerism*):

And um, with different bonds we have different strengths and .. depending on what's joined to it .. and um, what else, and the single bonds could rotate there [laugh] .. what else .. for the 2-butanol it comes with the OH's position .. at which carbon is positioned on, and um ... and you have all the other stereoisomers and that stuff. .. And um [laugh] ... And you can make them up with those I suppose. [he pointed at the ball and stick model] (Lee)

The responses in which the student recalled bits of the concepts introduced at the lecture and mentioned stability of different shapes were also included in this category (*Reminded of conformational isomers - Recall from lecture*):

R: Is it possible to convert one form to another?

Lee: Um, yes because bonds are free to move around. Depending on the kind of .. It could be either one of those at any particular time as bonds are rotating and they can rotate in between both of them. ... [laughs]

R: Have you ever heard about conformational isomers?

Lee: Yep, um you can get staggered ones, eclipsed ones, or just OH groups or other groups which are all close to each other but that is the most stable one, you can get anti ones and what do you call it GAU, gauche, that's used just to serve the positions of everything.

Finally, in the responses named *The only difference is conformation*, students described how the two structures drawn down at the supplementary sheet differ and identified or named the change using the term conformation:

They both have the same molecular formula and the same structural formula. They made up the same, the only difference between them is, oh, they are both 1-butanol, I think and ah the only difference between them is the conformation or where the OH groups position on a terminal carbon. And the top one, it's comes off at a different, well it goes up instead of down, the bottom one goes down. (Ken)

Discussing the similarities and differences between the two structures, three students pointed at the tetrahedral terminal carbon with no change in the shape between the two structures when the single carbon-carbon bond is rotated.

(b) Category Distribution Across the Participants

The different means of responding derived from the individual participants and in some cases one participant contributed to more than one category (Table 8.19.). However, when the quotes were taken back from the categories to the individual transcripts, it was possible to determine the category in which the individuals operated most. Table 8.21. shows the category distribution for the concept of conformational isomers across participants.

Table 8.21. The category distribution for conformational isomers across participants.

Category	No. of Participants
A	1
B	16
C	3
D	5

Pavlinic, 1999

When all the responses taken from the individual participant were reanalysed, it appeared that only one participant showed an unsatisfactory interpretation of the concept of conformational isomers (Category A). Sixteen participants were aware of the free carbon – carbon bond rotation, but were not able to assign it to isomerism (Category B). The responses, in which the participants talked about interconvertible shapes by the free bond rotation, indicated that a majority of the participants understood the concept underpinning the phenomenon, but were not able the link it to the conformational isomerism, even after being reminded. All these students showed a partially satisfactory conceptualisation of the phenomenon. It is a message to the

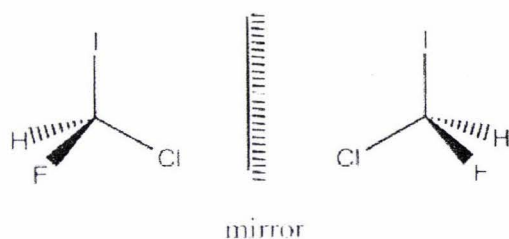
teachers that the link between the two must be more emphasised in teaching about isomers. The participants in categories C and D showed satisfactory conceptualisation of conformational isomers.

It was found that most students were not familiar with the term from high school, because conformational isomers are not the part of Bursary Chemistry syllabus. Three participants assigned isomerism when discussing the differences of two structures caused by the free bond rotation and four participants used the term conformational isomers. When reminded about conformational isomers, five participants confirmed while three denied that they had heard about this type of isomerism. The extent to which they described the term and assigned it to the shown structures varied. That depended on the time the interview was held (the beginning or the end of the course, i.e. the time the individual spent with the term - in lectures, tests, laboratory classes or revision). Due to the variable student exposure to the stereochemistry course materials (e.g. time spent in revision for the mid-semester test), the participants who were interviewed at the end of semester were found to recognise conformational isomers easier after being reminded of them compared to those who were interviewed in the first week of March (three of five participants whose conceptions were placed in category C were interviewed at the end of May).

(iii) Enantiomers

The students' awareness of enantiomers were explored according to their responses to the researcher-generated supplementary sheet with the nonsuperimposable mirror images of two structures as shown in Figure 8.4. The students were asked to describe the relationship between the two structures.

The distribution of the responses to different means for the selected participants is given in Table 8.22. The complete table is given in Appendix 5, (c) Analysis process - Step 6.



Payling, 1999

Figure 8.4. A copy of the supplementary sheet that was used to collect the participants’ conceptions of enantiomers.

Table 8.22. Selected participants’ awareness of enantiomers distributed to different means of responding.

Participant pseudonym / No. of transcript	Awareness of enantiomers					
	Not aware	Familiar –not able to name	Recognised and named		Shape/ stereocen. /atom size	Diff. prop.
Paul (2)				✓		✓
Ben (3)			✓			
Andy (7)				✓		
Jack (24)		✓				
Mark (25)		✓			✓	
-----	---	----	---	---	---	---
Rudy (1)			✓	✓	✓	✓
Tammy (4)		✓			✓	
Cara (12)			✓			
Meg (22)	✓					
No. of student responses / total	2	9	7	8	1	7

Payling, 1999

(a) Categories of Description

Further analysis resulted in four different categories of description in which students conceptualised enantiomers, as shown in Table 8.23.

Table 8.23. Categories of description for the concept of enantiomers.

Category/Referential aspect	Structural aspect
A - <i>Not aware</i>	No sign of understanding was shown. Participants did not show familiarity with the 3D structural representations separated by the mirror.
B - <i>Familiar but not able to name them.</i>	The participants demonstrated familiarity with the structures, described them as nonsuperimposable mirror images. A discussion about shape contributes to some descriptions. However, no clear evidence that the structures represent a type of isomerism was shown.
C - <i>Recognised as optical isomers or enantiomers.</i>	Apart from the description (nonsuperimposable mirror images), the structures were named straightaway either as enantiomers or optical isomers. Most of the descriptions involve discussion about the shape and the interpretation of the 3D structural representation (solid wedge, dashed wedge, lines). The influence of the atom size on the shape was also discussed.
D - <i>More complete conceptualisation</i>	The description with the more complete understanding of enantiomers involves recognition that enantiomers have different properties (rotate the plane of polarised light in different directions). In addition, as a support to the description of enantiomers as nonsuperimposable mirror images, the participants talked about stereocentre and gave an explanation why the two structures are nonsuperimposable mirror images.

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Category A – Not aware. In this category, students denied being familiar with the two structures shown on the supplementary sheet as mirror images of each other.

Category B - In this category, the responses named *Familiar, but not able to name them*, indicated that the participants were familiar with the two structures (one student confirmed familiarity but with no additional description and this response was excluded). Five students described the two structures as mirror images (mirror was on the diagram between the two structures) and four used the term nonsuperimposable. However, in this group of responses the students were not able to name the concept:

They are reverse of each other, um, I know that they are chemically like the molecular isomers but they have the same chemical formulae. Um, I know they are different but I don't know what to say about them to make them different ..
(Caly)

We did some of that one last year, but I am really bad in these things, names .. One is a mirror image of the other, they got the same atoms, .. they differ.. just sort of .. where about the atoms are like that .. you couldn't rotate it, if you rotate it wouldn't be the same .. and if you paste to each other wouldn't be the same either .. (Kay)

Category C - Most of the responses were grouped as *Recognised as optical isomers or enantiomers*. The participants described that they were familiar with the structures shown, mainly from their experience at high school. In their descriptions, they used the terms nonsuperimposable and/or mirror images and identified structures with no delay in their response either as optical isomers or enantiomers:

They are the mirror images, called optical isomers and they are, um, nonsuperimposable, they use the same number of atoms and the same types of atoms, um, yeah. (Ben)

or

Andy: Pretty familiar with those, enantiomers

R: When you are saying enantiomers

Andy: With the mirror between the two, they are mirror images of each other and also they are nonsuperimposable, so if I get this one here and put on top of that one they just won't superimpose .. yeah

Category D - In category D, the students' descriptions suggest that a more complete conceptualisation of enantiomers was achieved. The participants recognised and named this type of isomers (either optical isomers or enantiomers), in addition they mentioned how the two compounds represented by the structures differ in the way they rotate the plane of polarised light. The group of these responses was named *Enantiomers (optical isomers) differ in properties*:

They are optical isomers and one is gonna rotate the polarised light in one way, one in other way, yeah one to left, one to right, yeah. (Romy)

Ah optical isomers. They are basically the same structure and molecular formula, they are just mirror images of each other, and they are nonsuperimposable and you can't twist them around and replace them so that one is the same as the other one. And they rotate the polarised light. (Ken)

Some participants mentioned the term central atom or the term stereocentre in their description of superimposable mirror images:

Yah, OK, how we call them, enantiomers, another type of isomers, so they got all the same properties except they, .., they turn the polarised light in different direction, the thing I remembered, I listened in the 7th Form and the teacher had drawn them up in the board, we could see how they are not superimposable, ..

she had to use these [ball and stick models] to make molecules to actually show that they are different, yeah, so that's the thing about them, they are non superimposable, you know, like mirror images of each other and it only happens if you got the central atom with four different groups on the atom and, yeah .. (Paul)

Enantiomers. Ok they are, because this carbon is called stereocentre, that was a new word for me this year as well, um the carbons have four different atoms of, bonded to the carbon in the middle and they are, .. if you put a mirror between the two things, they are reflections in a mirror basically. Um, Um, Um, what else can I tell you, these we got in Bursary, they rotate the planar, this is about polarisation. Planar, polarised light ... Something, ... too many P's and too many L's I get lost, but yeah. (Rudy)

They are enantiomers, three dimensional representation is shown, they are nonsuperimposable mirror image of each other, because of stereocentre, that is what is called when four different groups come off it and they rotate the polarised light the same amount but in a opposite direction to each other. (Steve)

As a contribution to the categories most of the participants talked about the shape, tetrahedral carbon and the 3D structural representation in which different lines (normal lines, dashed and solid wedges) are used in an attempt to indicate the spatial three-dimensional orientation of the groups surrounding the stereocentre. The tetrahedral shape of the stereocentre was recognised by most of the participants, while some discussed the atom size effect on the tetrahedral shape of the stereocentre:

If these four are bonded to it would be tetrahedral but the different sizes of the atoms may effect not be exactly tetrahedral, even though there is four attached to it, the atom size would effect the tetrahedral shape.. (Lee)

Um, the chlorine and iodine will dominate cause they are a lot larger, so that will be seen, quite obviously, the hydrogen will be very small and hard be able to see the carbon I suppose because .. the iodine will, sort of, cover over it [carbon]. That's, sort of, vaguely what I think of overall. (Eddy)

It might be that the 3D structural representation itself initiated the participants to discuss the tetrahedral shape of the chiral carbon or stereocentre.

(b) Category Distribution Across the Participants

Table 8.24. shows the results of the attempt to distribute categories of description across the sample of the participants.

Table 8.24. The category distribution for enantiomers across the participants.

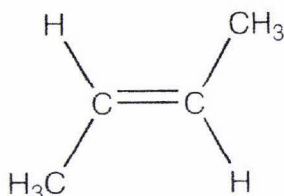
Category	No. of Participants
A	2
B	6
C	11
D	6

Pavlinic, 1999

In conclusion, two of the participants did not give a satisfactory description of the concept of enantiomers. In addition, the responses from six different participants in the group *familiar – not able to name them* had not given an evidence of satisfactory conceptualisation of enantiomers. The responses of the rest of participants (those assigned to categories C and D) indicated a satisfactory conceptualisation of enantiomers.

(iv) **Cis-Trans Isomers**

The participants were shown a supplementary sheet as shown in Figure 8.5.



Pavlinic, 1999

Figure 8.5. A copy of supplementary sheet that was used to collect the participants' conceptions of diastereomers.

Responses with no delay and comments such as “pretty familiar with that structure” (Ben) or “Yeah, the *cis-trans*, that is the *trans* form. Yeah, um, we had it in Bursary exam.” (Ken), or those that involved a naming of the chemical compound as a first response “It’s a *trans* butene, isn’t it?” (Erica) or “It’s *trans* 2- butene, so it’s the smallest possible *trans* ..” (Eddy), suggested that most of the students were familiar with this type of isomerism from high school (only two of the students responded as not being familiar with the structure shown on the supplementary sheet). The *cis-trans*

isomers were easily recognised because of the double bond and the arrangement of other groups around the double bond. An awareness of no rotation about a double bond was present in most of the students' descriptions (sixteen students were assigned to this group of responses). Nine students talked about the shape and how no additional or three-dimensional representation for this type of isomerism was required due to the trigonal planar shape of the double bond, therefore it can be faithfully represented in two-dimensional structure.

The summary of individual student responses to different means of responding for *cis-trans* isomers for the selected participants is given in Table 8.25. The complete table is given in Appendix 5, (c) Analysis process - Step 7.

Table 8.25. Selected participants' awareness of *cis-trans* isomers distributed to different means of responding.

Participants pseudonym/No. of transcript	Awareness of <i>cis-trans</i> isomers							
	Not aware	Aware / confused	Double bond			Naming		
			No rotation	Planar	Properties	Geom.	Diast.	Ster. Config.
Paul (2)			✓					
Ben (3)			✓			✓		✓
Andy (7)			✓		✓			
Jack (24)	✓							
Mark (25)			✓					✓
-----	---	---	---	---	---	-----		
Rudy (1)			✓					✓
Tammy (4)			✓	✓				✓
Cara (12)			✓					
Meg (22)		✓						
No. of student responses / total	2	2	16	10	4	2	1	1 3

Pavlinic, 1999

(a) Categories of Description

Further analysis resulted in four different categories of description in which students conceptualised diastereomers, as shown in Table 8.26.

Table 8.26. Categories of description for diastereomers.

Category/Referential aspect	Structural aspect
A - <i>Not aware</i>	The structure shown did not appear familiar nor initiated the participants to discuss the possible arrangements of atoms/groups about the double bond.
B - <i>Familiar but confused</i>	The participants demonstrated familiarity with the structure shown, brief description on what they had seen was given (double bond) but were not able to name them. Awareness of isomerism but confusion with the terms and the concept (no evidence of understanding for this isomer type was shown).
C - <i>Recognised as cis-trans isomers</i>	The participants showed familiarity with the structure straight away, gave the proper chemical name and talked about <i>cis-trans</i> isomers. Description based upon discussion of the shape of the double bond, no rotation of double bonds, the chemical terms used date from high school.
D - <i>More complete conceptualisation</i>	More complete understanding of diastereomers involving the recognition that these stereoisomers differ not only in the structure but in properties as well; also the classification of <i>cis-trans</i> isomers into diastereomers and configurational isomers was found in the participants' descriptions.

Excerpt 1999

Category A - Not aware. Only a couple of students stated that they were not familiar with this type of isomerism. For example Amy started with a description "It's got a double bond between the two carbons (20) and I'm not really sure, I think, possibly the methyl group does something, I don't know". Having only the *trans* isomer of 2-butene, she was led to draw its *cis* isomer. When asked to describe the difference between the two she answered:

Amy: Um, .. not sure, I think it is different to that one ..

R: Have you heard about *cis-trans* isomers?

Amy: *Cis-trans* isomers, I suppose

However, Amy was not able to make any additional comment.

Category B – *Familiar but confused with the cis and trans isomers*. The description below demonstrates familiarity with the structure, but no understanding of the *cis-trans* isomerism was demonstrated:

R: How would you describe this structure?

Jack: Oh, yeah, well, basically it has a four-carbon chain with a double bond between the second carbon and the third carbon ...

.. [he did not mention *cis-trans* isomers on his own, so he was gradually led to

draw the *cis* isomer]

R: What about another structure having the same double bond and this CH₃ group right on the top and this H on the bottom? Could you draw it for me please?

Jack: Sure. So, both CH₃'s are on the top, oh well, .. I actually wasn't sure, I realised that is carbon that is attached.. not a very pretty diagram but

R: How the two structures relate to each other?

Jack: Well, one is the isomer of the other, what I can tell you about? .. [then he recalled] *trans* and *cis* isomers, .. again, I have to admit that I am awful with, you know prefixes you know butanol, ethanol et cetera and I can never remember without looking, aaah, which one is *trans*, which one is *cis*, possibly because I am just lazy, I always look at the notes.

R: Are you aware about them?

Jack: *Trans* and *cis* isomers, yeah, but if you ask me which one is *trans*, which one is *cis* I wouldn't know ..

Category C – *Familiar, easily recognised and described as cis-trans isomers.*

Familiarity with the structure was shown straightaway, often supported by a smile or an expression of relief. The participants gave the proper chemical name to the structure shown and talked about *cis-trans* isomers. Description was based upon discussion of no rotation of double bonds. In describing this type of isomerism, the terms other than *cis-trans* isomers (e.g. diastereomers or configurational isomers) were used by only a few participants.

Up to the point of being introduced to the sheet showing the compound with a double bond, the students often talked about the flexibility of a molecule and about single bond rotation (see section *Conformational Isomers*). Therefore, it was not surprising to find discussion about no rotation about the double bond contributing in many descriptions in this category. This was seen as a continuum or a reflection of the discussion given earlier during the interviews. The selected episodes below show that students, familiar with *cis-trans* isomers, in their very first response mentioned *Double bond - No rotation*.

An alkene with a double bond, it's a *trans* isomer of it, because of opposite occupied sides of double bond and you can't really rotate the carbons cause the double bond stops that. (Kay)

This is a .., I can't remember the heading for these either, it's a *trans* isomer, you can have *cis* and *trans* isomers. Um, when there is a double bond between two carbons and you've got two different groups coming off each, of each carbon, and yeah, so the *trans* means the groups if it is the same, of each carbon are on opposite side and they can't change between each isomer because the double bond doesn't allow rotation to occur .. (Paul)

Category D – The more complete description assigned to this category contained the quotes in which the other properties of the double bond were discussed. The description is enriched by the explanation given why there is no rotation of double bonds. In addition the participants talked about the shape of double bond:

Ben: Yeah, I am pretty familiar with that too. It's an alkene, yeah, the double bond we can't rotate it, the bond is **short**

R: Why is that?

Ben: Oh, it's cause it's two bonds between them and that sort of force them together, you can't rotate, um, carbons don't have, they are still three bonds but two of them are taken up by the double bond so therefore there is only two available for other bonds between, I think it's flat and yeah. ..

Yeah, that's *trans*, and you can make a *cis*, *cis* one by putting that down and we actually got that

Andy: That sort of an alkene .. and is a butene ... and would be no rotation around the double bond there

R: Why is that?

Andy: To rotate the double bond you would need to break it, the bond break

R: Is it possible to draw the structure different from this one?

Andy: Yeah, you could have, this one is a *trans* isomer of butene, you could have a *cis* isomer where both methyl groups were on the same side of the molecule, at the moment they are at opposite sides

Andy described that the double bond has to be broken to make rotation possible. Dan discussed how the *cis* and *trans* isomers are not convertible from one to the other “.. but it needs a lot of, heaps of pressure because you have to break the pi bond, .. the pi bonds and anything that stop to change that in that, that's why they are different, because of pi bond”.

When discussing double bond properties in the quote given above Ben said: “it's flat”. A discussion on the effect of the presence of a double bond on the shape often occurred in the student description. The shapes shown by different structures had been discussed earlier during the interview protocol. Jody used the ball and stick model to investigate the shape of a compound containing double bond, and her response belongs to the group of responses derived from nine students that described *The planar shape and no rotation of double bonds*.

There is no rotation about the double bond, you can break it to rotate it but there is no free rotation around the bond because the way the pi orbitals sit, that was last week's lecture..

The shape, ah, it's trigonal planar around these carbons, .. I think, .. let's have a look, again you see I use model stick to see how is gonna look like .. (Jody)

Many students recalled the chemical terms from high school. However, seven students tried to recall information about the concept given at a recent lecture and even mentioned different properties. Two participants used the term geometrical isomers. Only one of the students used the term diastereomers. It appeared that the term diastereomer is a much more alien term compared for example to the term enantiomer. Three students classified these isomers as configurational isomers, and one classified them as stereoisomers.

Recall from recent lecture: Diastereomers with different properties

Martin: This diastereomer with *trans* ..

R: You used the term diastereomer ..

Martin: Yes, during my lectures, tutorials, ... you know there is no bond rotation with the double bond. That would make this different to *cis*, that would make them different, where is for a normal single bond you take a rotation around a bond, so they wouldn't, so they wouldn't have different properties

Cis-trans isomers - classification into the Configurational isomers

Tammy: That's a *trans*-isomer, so it is configurational I suppose, and it's got um, it's got a double between the two carbons, so there shouldn't be too much rotation happening, um, .. yeah .. it's got no functional groups on it or anything. It is pretty plain and straightforward. It's a butene so um, there is a carbon chain with a double bond on it. .. Um, yeah it's got to be the same as like, oh this is trigonal axis I think and um.

R: Why trigonal?

Tammy: Um, when you have a double bond definitely because when you go to a triple bond it goes linear because just how it moves somehow, and with this one if the double bond um is, something to do with p-orbitals and it stops them from rotating and so it's, I think what is that word, um it's something like three of them coming out because there is a double bond here I think and so it makes a trigonal and, yeah, I'm not sure.

Yeah, it's a 2-butene, it's in a *trans* configuration, is that? Yeah, *trans* because one is coming down, one is coming up from inside of double bond, the *cis* would be this would be down here and the hydrogen up here, um what else (Dan)

(b) Category Distribution Across the Participants

Table 8.27. shows the results of the attempt to distribute the identified categories for diastereomers across the sample of the participants.

Table 8.27. The category distribution for diastereomers across the participants.

Category	No. of Participants
A	2
B	1
C	14
D	8

Payline, 1998

In conclusion, the two participants who admitted not being aware of *cis-trans* isomers (diastereomers) in category A were classified as not showing satisfactory interpretation related to diastereomers. From the two participants who admitted being confused with *cis-trans* isomers, differentiation was made between whether they were confused with the concept or they just mixed up the terms *cis* and *trans*. The latter analysis identified that one of them was indeed confused with the concept (category B), but the other participant gave a satisfactory description later and showed confusion only with the terms *cis* and *trans*:

It's an alkene, double bond, its a *trans* [laugh] I am thinking that it is, if you have *cis* and *trans*, I have always had trouble to tell difference between them, I am thinking it is going to be *trans*?..

And it's two, it's a but-2-ene *trans* yeah, get this right, *trans* but-2-ene I think. And um, yeah basically, no rotation happens around the double bond there. Um and that's like having a *cis* and *trans* things. I think they are called, that's either a conformational or configurational isomer, I think it is a configurational or what, I'm not sure why. Um [laugh] I need to study that one up fully. [laugh] (Rudy)

Therefore three participants were assigned as those who did not demonstrate a satisfactory conceptualisation of the *cis-trans* isomers, while all other 22 participants demonstrated satisfactory conceptualisation of this isomer type.

(v) Discussion

The analysis of the students' awareness of each type of isomerism was based upon the students' discourse and what students highlighted in their responses to issues raised during the interviews. For each isomer type, the participants' descriptions were categorised into a hierarchically ordered categories of description.

The summary of the main responses to different isomer types, that could be relevant to

teachers teaching these concepts, is given in Table 8.28.

Table 8.28. The summary of the students' main responses to different types of isomerism.

Type of Isomerism	Familiarity	Chemical Terms	Description
Structural (Constitutional)	✓	✓	Different arrangement within the same group of compounds (Category B)- needs to be addressed in teaching , More complete understanding includes awareness of different physical and chemical properties.
Conformational	x	x	Free bond rotation - the same structure (not assigned to isomerism) (Category B) – needs to be addressed in teaching . Recall of terms from lecture and assigning isomerism.
Enantiomers/ Optical	✓	✓ ✓ / ✓ ✓	Mostly named, nonsuperimposable mirror images, stereocentre, tetrahedral shape, property - rotation of the plane of polarised light.
Diastereomers/ <i>Cis-trans</i>	✓	x / ✓	Readily named as <i>cis-trans</i> isomers, but seldom classified as diastereomers or configurational isomers – needs to be addressed in teaching Different properties of double bonds - no rotation of double bonds, planar shape, but no discussion about different physical or chemical properties of these isomers.

Parlinic, 1999

- ✓ easily recognised and described
 ✓ ✓ recognised, described and preferred
 x not recognised, described or used

The findings suggest that the participants in this study appeared to be more familiar with some types of isomerism than others. This familiarity mainly originated in prior knowledge brought from high school, with not many participants being able to recall the recent lectures at university. Familiarity did not mean that the students always understood a certain type of isomerism completely as quite often their description only partially matched the accepted scientific explanation for that type of isomerism, for example, the findings in which students only described structural isomers belonging to the same group of organic compounds (alcohols) as identified in category B for structural isomers. Similar findings were reported in the study by Schmidt (1992), though the author investigated high school participants and used different methodology. The agreement in the finding is not surprising as the concepts of isomerism that were disclosed in this study are mainly based upon the students prior knowledge, developed

at high school.

To some participants, high school experience has not been, as Jack described, “a big deal” in their conceptual development of isomerism:

Well. Yeah, *cis* and *trans* isomers came up a bit there [high school], but not much really. It wasn't a big part of it. The small, like the teacher introduced it because we will come in it later at university, not so much, because it wasn't really relevant to the material we have been taught then, but, yeah, we covered down, you know, nonsuperimposable mirror images, *trans* and *cis* isomers, that other came, um, yeah. (Jack)

In addition, this judgement of a satisfactory description or conceptualisation does not mean that the understandings of a certain concept of isomerism were evaluated. Although the interview questions aimed to investigate student conceptions of different isomer types were exploratory in nature, this exploration was only a part of the phenomenographical interviews that complemented the investigation of the students' visualisation. The limitations of the findings are due to the small number of the participants and because the responses for some isomer types (enantiomers, diastereomers) were mostly collected from the participants' description of the structural representations shown on the supplementary sheets. The interview time limit did not allow any further exploration. It is important to point out that a molecule of 2-butanol was chosen because of the opportunity to explore both structural isomers and enantiomers. However, none of the participants mentioned the idea of enantiomeric possibilities of 2-butanol and the insights for this isomer type were collected through the participants' responses to the supplementary sheet only. Therefore, these findings could be used only as an indication but not as evidence of the understanding of the concepts of isomers.

(a) *Language*

The interview transcripts disclosed that most of the students' awareness of isomerism dated from their knowledge from high school. However, the terms used to describe the concepts of stereoisomers differed amongst the participants depending on whether or not and for how long the participants were exposed to the concepts at university. The interviews were held at the beginning of the semester when the stereoisomeric concepts were just introduced and later on during the semester towards the end of the course (during which the students had an opportunity to do a revision for their mid-semester

test). Students interviewed at the beginning did not show familiarity with terms such as conformational or configurational isomers, enantiomers or diastereomers. Instead they readily talked about optical isomers or *cis-trans* isomers, which are chemical terms taught at high-school (only one student, interviewed before the lecture covering the stereochemical concepts, used the term stereoisomers).

The analysis of the transcripts from the interviews held later during the semester disclosed that students struggled with “the actual terminology”. Dan described:

I forgot the actual terminology for them, but they are type of isomers, mirror images and nonsuperimposable of each other, and also this is a stereocentre, so they are enant, some with enant, enantiomers, strength each ups?? .. [laughs]
(Dan)

Others confirmed their familiarity with the new terms introduced during the course like Andy whose first response to the sheet showing the enantiomers was “Pretty familiar with those, enantiomers” or Eddy who explained “They were new this year but I am familiar with them now.” Describing enantiomers Rudy mentioned how the “stereocentre, that was a new word for me this year as well, um ..”

While many students used the term enantiomers, only one participant classified *cis-trans* isomers into the diastereomers. For this type of isomerism four different terms were used by the participants (see Table 8.25.) Furthermore, a very few students distinguished conformational isomers from configurational ones. It appeared that these new terms must be learned together with the concepts and that takes time until the students assimilate and become familiar with the new terms.

(b) *Isomers –The Big Confusion*

The study disclosed the confusion both with the appropriate use of stereochemical terms and with the meanings of the terms used. Quite often the meaning of one term is mixed up with the meaning of another and successful familiarity with one term required repetition.

The following inserts from Tammy’s interview transcript disclose her confusion about what to choose from the broad range of possible terms or explanations available. Is it an isomer? If so, what kind of isomer that would be? Looking at the structures she articulated:

Ok um, the only difference is the place of the OH, the alcohol group, it’s

coming off the carbon at a different, um still the same carbon but it is coming off at a different spot on the carbon and I guess ... um, it's like all the chains are the same apart from the very end carbon and it's got the two hydrogens, would it be, it might be something to do with *cis* and *trans*, maybe I don't know, this would be like, it's got it coming off here and that is like a *trans*, the two hydrogens, and if it was *cis* it's got the two hydrogens going up in this direction. Um but I think it is generally bigger, if they were um, more bigger functions than just hydrogens. Um, I guess it does react differently, but it's a difficult question because it will still come out of the same carbon. If it was like in here, in the middle of the chain, in here, it's going to be a different isomer, it's going to react differently but, being on the same carbon um, it also means like, when you look at the ball and stick model that it's going to be, but they will be rotating around won't they, so, with the OH on it so it really doesn't make a lot of difference. I'm just trying to clear this in my mind. This is the carbon here and you have got your alcohol, you've got this, yeah you come off, this one on here, it's all going to be, at one stage it's like there's your OH and the other hydrogen at the top and a hydrogen down here and at the other stage it's just down the bottom. But if this is rotating all of the time then it shouldn't make a lot of difference. I don't know if that is right or not, but ..(Tammy)

Later on, when asked if she has heard about conformational isomers she confirmed:

Yeah. And configurational isomers. Conformational is that the mirror image ones? .. Um yeah, I think it is the where it is a different mirror image of it, but it's different and that makes a difference so then this might be one. I don't know .. (Tammy)

When the sheet with two structures in a mirror relationship was shown to her, the confusion was even greater:

Ok, well they have got um, ... I should have done some study. It's the same kind of, there is the carbon there, it's the same bend of the carbon with the same things coming off it but it's, it's like it's got a mirror between them and so it reflects things differently and it's superimposable, I'm not to sure what that actually means, I must say. Yeah. I think I will stay clear of that question. I don't know. (Tammy)

It seemed as though she gave up trying to pick up appropriate information from a basket containing a lot of unknowns (unknown concepts and unknown terms all mixed together).

It would be expected that the participants whose ways of visualising molecules were classified into higher categories of description would demonstrate a more developed understanding of the concepts of different isomers as well. And for some of the participants that was the case. In general, the agreement depended on the time of the semester the interviews were held. Interviews were held throughout the semester, so the

participants who had been interviewed at the early stage (start) of the semester had not been exposed to the concepts of stereoisomers as long as the participants who were interviewed towards the end of semester. The time spent in dealing with stereoisomers influenced the student conceptualisation of each isomer type.

The ways in which the participants described their visualisation of molecules (e.g. of 2-butanol) were products of their learning and the teaching of chemistry accumulated over a period of time, at high school and further developed at university. The learning about isomers was not a similar case. Many participants left high school without an adequate background of some isomer types, even the types of isomerism that appeared more familiar to the participants such as structural isomers. The identified misconception seems to date from the high school instruction and, as found in this study, satisfactory conceptualisation has not been developed even after exposure to university lectures. Exposure to lectures in which students have to listen and understand, but also take notes, does not always help learning. Paul described:

Um, .. mainly I just listen to my teachers or lectures, um, I don't do much reading about it, I often find using, I guess, someone else's ideas, they tell me what they think and then you just develop in to use this, um, I learn best I think by listening and remembering everything .. or even take notes and read them later, I am always best to sit and listen them the first time, sort of thing, yeah.
.. Yeah, um, I guess, I think, .. something that matters is, there is the pace of, I notice the main is ... I mean I just changed lectures in the chemistry class and the lecturer goes a lot faster, covers the stuff faster. I like to take good notes, but I like to listen more than I like to take the notes and it's hard to get something down and still listen to all he is saying, he is jumping from one thing to next, yeah, probably wouldn't harm if they talk a bit slowly and giving me time to write things down ..

While listening to the lecturer and, as Paul described, "someone else's ideas", help Paul to develop his own understanding and is in agreement with Vygotsky's sociocultural philosophy of enculturation, most of the students are concentrated on taking notes during the lectures. From the point of information processing theory, Johnstone (1997) argues that in a lecture all the student's working space is "devoted to transferring the spoken words to notes and very little or no understanding takes place at the time" (p. 45.).

The findings suggest that one of the main factors that influenced students' conceptualisation of isomers seems to be the limited time the learner spent in dealing with the concepts. Thus, many different meanings and terms required time to be spent in

dealing with them. An example is Mark, the participant who was interviewed first and before the lectures on concepts of stereochemistry were introduced at university. The selected quotes, which indicated the ways he visualises molecules, were assigned to the highest category. However, his responses to the supplementary sheets suggested for example, that until that time he had never heard the term conformational isomers, he was aware of stereoisomers and of *cis-trans* isomers being stereoisomers, but he has not shown familiarity with terms such as enantiomers or diastereomers. Tammy was the participant with the most responses to visualising molecules allocated to category C. The descriptions of the ways in which she conceptualises different isomers suggest that she was very confused with different isomer types. In addition, it is worth mentioning that she was also interviewed at the start of the semester.

(c) *Properties of Isomers*

Not many students mentioned different properties either of structural isomers or stereoisomers (six of the students were aware about different physical and chemical properties of structural isomers and five students were aware of the optical activity of enantiomers). The students' descriptions were focussed more on explaining how the structures differ in their symbolic representation. This is not surprising as the symbolic ways of representing organic compounds were given to students to initiate students' responses such as to recognise, identify and talk about isomers. Also, not much discussion of isomers with regard to their stability was found in students' discourse. However, having the ball and stick model of 2-butanol they had made, the students were asked: "Can you put the red oxygen somewhere else?". The responses varied from those who discussed the different properties (reactivity) if the -OH group was on the second carbon, to those who talked about different arrangements leading to different compounds with different chemical and physical properties. Student responses in which they mentioned properties were placed in a group of responses classified as more complex awareness of structural isomers.

However, properties are seldom mentioned in the discussion of the other types of isomers. Stereoisomers were mostly described as having the same arrangement of groups or atoms but different spatial orientation (conformational isomers, enantiomers or *cis-trans* isomers). From all of the students' responses and across all of the different groups of stereoisomers that were investigated, five students mentioned the optical

activity of enantiomers and only two participants mentioned that *cis-trans* isomers might have different properties.

It is most likely that the recall of optical activity of enantiomers has occurred due to the description of this property being a part of the definition of enantiomers which the students were taught at high school.

(vi) Conclusions

The results of this part of the study disclosed that the students showed different familiarity with different isomer types. The participant conceptions of each isomer type depended on the student's prior knowledge (the lack of familiarity with some isomer types such as conformational isomers and with some terms such as diastereomers was noticed amongst the individual participants who were interviewed before, during and after the instruction was given at the lecture).

For structural isomers, it appeared that teachers should pay attention to the conception as identified in Category B in which the participants assumed that structural isomers should belong to the same group of organic compounds. This conceptualisation was assigned as unsatisfactory understanding of the concept.

For conformational isomers most of the participants described that one shape of the structure could be converted into the other by free single carbon-carbon bond rotation. However, a very few assigned it to isomerism (Category B), which was also identified as an area to be addressed in teaching.

Optical isomers were recognised due to the mirror images with less than a half of the participants being familiar with the term enantiomers. This was the type of stereoisomerism to which students in Category D assigned the property of the rotation of the plane of polarised light. This insight will be used later in Study Four.

Finally, *cis* and *trans* isomers appeared as the type of stereoisomerism that most of participants were most familiar with (just two students admitted not being familiar with this type of isomerism from high school). However, unfamiliarity with the terms and classification to the diastereomers and configurational isomers has also been identified and this insight should be emphasised in teaching of this concept of isomerism.

The conceptualisation of different isomer types was based upon the description of the structural representations and the terms describing them. Students rarely alluded to any

difference of isomers based upon a macroscopic dimension of chemical compounds (physical or chemical properties). Apart from talking about different properties of different compounds (structural isomers), the single property that was found in students' responses to stereoisomers was the optical activity of enantiomers. It was suggested that the conception of the property of enantiomers added to the rest of description occurred because of the way students have learnt about enantiomers (definition of enantiomers given in the high school chemistry textbooks). This raised the issue that the properties of isomers including stereoisomers other than the one given in the definition of enantiomers should be more emphasised in teaching chemistry.

8.6. PHENOMENA ONE, TWO, THREE - SUMMARY

The results in which the ways of visualising molecules were given (Phenomenon one) showed that a majority of the students employed the use of symbolic and/or micro representations/models in describing the ways in which they visualise a molecule of 2-butanol. The ways in which the students described their visualisation of a 2-butanol molecule generally agree with the observation made by Johnstone (1999) in which he commented: "Ask students to write down their immediate response to the word 'benzene' and you will get ' C_6H_6 ' or 'a hexagon' or 'delocalisation' or 'aromaticity', but seldom will get 'a colourless, carcinogenic, flammable liquid'" (p. 46). The notion of the observable nature of 2-butanol was present in the description of only one participant, who replied: "2-butanol is a liquid, isn't it?" This participant was a mature student and it might be that the experience in chemistry he had gained over time enabled him to naturally integrate the observable level of chemistry more easily than others. This is in line with the philosophical view that the ability to integrate abstract and the observable concepts in science come naturally only with experience (Lemke, 1994). The ability of this student to think at the macroscopic, observable level was confirmed throughout the interview.

If the micro and symbolic, two predominant ways used by students to describe the visualisation of the organic molecules, fit into the two corners of the well established micro-macro-symbolic Johnstone's triangle, then the 'real' liquid shown to students represents the third, macroscopic dimension and fits into the third corner of the triangle. Student ability to articulate, switch and integrate these three aspects of chemistry was the aspect of analysis (Phenomenon two) employed in this part of the study.

The findings of the students' ability to associate the real liquid to the ways in which they described visualisation of the molecules were presented in a form of hierarchically ordered categories of description. The range of the students' verbal responses to the appearance of a 'real' liquid during the interview, which was held in the frame of talking about chemistry in 'commonly known terms', was disclosed. Within the range of these responses most participants recalled and discussed the microscopic nature of chemistry (category D2).

However, the diversity of the students' responses to the sight of real liquid revealed the complexity of the ways we all think about chemistry. An additional insight emerged from rereading the student transcripts, in which the emotional responses such as surprise, even shock, were added to the very diverse verbal responses. The new insight suggested first, that everything the student might know in chemistry is dependent on what he or she might have been taught (enculturation into chemistry), and second, that the 'real' chemistry is kept very separate and distant from the chemistry being taught to student.

This new insight into the human understanding of chemistry is introduced as a **dream world-real world** concept. The 'dream world' concept represents the body of knowledge which must be taught in chemistry and involves a construct developed to provide a framework to understand the 'real world' that is all around us. On the other hand, as described by the participants, the 'real world' of chemistry does not exist easily or at all in their 'dream world' of chemistry but somewhere else, in places like laboratories.

The purpose of this part of study was to find out whether there is any link between how well a student appears to operate in his or her dream world (visualising molecules) and the ability to relate it back to a real world. It might be anticipated that according to Lemke (1994; 2002), with maturity and after years of experience it becomes easier and more comfortable to work at the real world - dream world interface as chemists do.

Although one might argue that the students' experiences of laboratories reflect the structure of tertiary teaching, from the perspectives of the 'dream world – real world' concept, the ways in which the participants experienced laboratory classes as distinct from the rest of the course seem reasonable. Similarly, the new concept could be used to interpret the students' conceptualisation of different isomer types, which rarely included the awareness of the macroscopic aspects (different properties).

The findings of the participants' conceptions of isomerism (Phenomenon three) showed a range of the categories for each isomer type. Analysis of the ways in which the participants conceptualise each type of isomerism was based upon a description of the structural representations, a discussion of the spatial orientation of the groups, the shape of the tetrahedral carbon surrounded by single bonds compared to the shape of double bonds including terms describing them. The participants rarely discussed the difference between isomers based upon a macroscopic dimension such as physical or chemical properties. Apart from talking about different properties of different compounds (structural isomers) that was identified in the highest category D for structural isomers, the property that was most often found in students' responses for stereoisomers was the optical activity of enantiomers (also category D).

The conceptions of visualising molecules were generally analysed from the whole interview with many contributors being examined (involving the student responses to the 'real' liquid). Generally, an agreement was found between the visualisation of molecules and the ways the students related the macroscopic substance to their visualisation (low-moderate-developed). However, the agreement of the ways in which the participants described their visualisation of the molecules and their conceptualisation of each isomer type depended on when the interview was held during the semester. While the visualisation of molecules was more influenced by the ways students were taught chemistry at high school, their awareness of isomerism and particularly association with the appropriate chemical terms depended more on what the participants were able to recall from the recent lectures at the undergraduate level. Still, due to the small number of the participants, these findings cannot be generalised.

The student visualisation of molecules and their learning of stereochemistry mirrored the contribution of different approaches to learning combined together (a surface approach and memorisation necessary to cope with the course requirements, a deep approach when seeking for an understanding of the ideas for oneself, but also a strategic approach to achieve the highest possible marks).

8.6.1. Implications of the Results in the Tutorial Revision

Study Three was the part of the project aimed at exploring students' conceptions underpinning their understanding of stereochemistry – a topic that was addressed by the in-house developed computer-based tutorial (described in Study Two).

The results of Study Two showed that students had most difficulties in solving stereochemical problems involving complex molecules (e.g. Exercise Two). It could be that the representations employed in the tutorial design (skeletal structures and the ball and stick models) did not match with student visualisation of complex molecules. The study of the ways in which students visualise molecules (Phenomenon one) informed the researcher that the structures showing all the atoms present and the types of bonds are the ways most students described their visualisation, either verbally and/or in a form of drawings. Such kind of representation of the molecules was identified to be the most familiar to most participants.

In order to give students more confidence in the tasks that involved complex molecules, it was suggested that an adaptive feedback for the tasks that involve complex molecules should have additional representations that explicitly show all the atoms present in the molecules. The added, more familiar representation could provide a better match with the student visualisation.

The tutorial that was designed in Study Two was aimed to follow the instruction given at the lecture. From the perspective of the ‘dream world-real world’ concept the tutorial provided the students with the opportunity to enrich or widen their ‘dream world’ of stereochemistry.

In order to bridge the gap between the ‘dream world’ and the ‘real world’ of stereochemistry, one possibility was to integrate the ‘real world’ aspect of stereochemistry into the tutorial and that possibility was undertaken in the next study. Another possibility was to design a new tutorial looking at how the isomers are determined, and so bring out the macro-micro interface.

If stereochemistry is taught to students in a way that integrates the two worlds, it is more likely that the gap would not be as wide as appeared from the results of the present study.

Finally, the results of the Phenomenon three of this study, which explored student conceptions of different isomer types, revealed students’ difficulties in conceptualising and naming different isomer types. In addition, not many students were aware about properties of isomers. In order to help students to develop their conceptualisation of isomers more than hitherto, in their instruction teachers should emphasise properties of isomers.

8.6.2. Implications of the Results in Teaching Other Chemistry Concepts

The study that explored the ways in which students visualise molecules is important because visualising molecules underpins not only the understanding of stereochemistry but also the understanding of most concepts in organic chemistry and biochemistry. Therefore the outcomes may be used to inform teachers in teaching many chemistry concepts.

The overall results of the present study suggest that the most significant dislocation in learning chemistry seemed to be between the world of real substances ('real world') and the body of theoretical knowledge the students are taught ('dream world').

The schism of the 'real world – dream world' concept in student understanding of chemistry that was discovered in the context of exploring student conceptions, important in their understanding of stereochemistry, is not stereochemistry specific, but can be used as a possible explanation for learning difficulties observed for other chemistry concepts as well.

Therefore, the message to teachers is that the teaching of chemistry must attempt to take account of this schism and take every opportunity to attempt to bridge it either during the instruction of new concepts or after the concepts have been mastered and need to be applied in a real world situation.

The present study was carried out to check and additionally inform the design of the stereochemistry learning tasks in the computer-based tutorial, however the results should be considered in designing learning tasks using educational tools other than computer-based tutorials.

The results of the present study in which the participants employed microscopic models in describing the real liquid indicate that an appropriate instruction can influence the student's 'dream world' of chemistry.

Recognition of the difference between the microscopic and symbolic aspects of the body of chemical knowledge and the emphasis at the molecular level in describing chemical phenomena were found useful and contributed to student visualisation of molecules. It is suggested that the integration of the world of real substances with the rest of the body of chemistry knowledge in teaching could initiate the students to bridge

the gap between their ‘dream world’ and their ‘real world’ of chemistry.

Finally, it is worth mentioning the role of phenomenography which was employed in this study. Not only the outcomes in a form of categories of description that are given, but all other additional insights would not be revealed without the contribution of the phenomenographical interviews.

9. STUDENTS' RESPONSES TO THE AMENDED STEREOCHEMISTRY TUTORIAL – STUDY FOUR

Study Four was conducted in two phases. In the first phase, the findings of both Study Two, in which student interaction with the tutorial was initially examined during the tutorial development, and Study Three, in which the students' ideas of the concepts underpinning their understanding of stereochemistry, were taken into account in the amendments of the tutorial.

In the second research phase, student interaction with the amended tutorial was explored. The research focussed on how well the amendments of the tutorial were received by the participants and if they had made any changes in students' use of the tutorial and their achievement of intended learning outcomes of the concepts covered by the tutorial.

The research design involved the use of the techniques used and described in Study Two. For that reason only the changes made in this study are described.

9.1. REVISION OF THE COMPUTER-BASED STEREOCHEMISTRY TUTORIAL

In the tutorial revision, two levels of the amendments have been made, minor and major.

9.1.1. Minor Amendments in the Tutorial

The label 'minor' was not used to diminish the importance of these amendments to the tutorial: it refers to the amendments in the three exercises in which the design of the tutorial (structure, concepts, tasks within each exercise etc.) was kept as originally designed. The aim of these simple amendments was to provide better delivery of the instruction designed in 1998 and therefore to improve the students' use of the tutorial.

The findings of Study Two, which explored student interaction with the tutorial, originally designed in 1998, showed which aspects of the tutorial design failed in

providing the students with the intended student-tutorial interaction and where the students had difficulties when interacting with the tutorial. The insights below were used as targets for the amendments:

- Inadequate use of glossary;
- Clarity of the instruction given prior to Exercise Three;
- Use of hints available in Exercise Three;
- Difficulties – the representations of the tasks involving more complex molecules.

In addition, the findings of Study Three were examined to check if the representations used in the tutorial matched the ways most of the first year undergraduates visualise molecules.

Some amendments were specific for the particular exercise; some were common to all exercises. The description of the amendments is given below.

More familiar representations. The results of Study Two indicated that to most participants, both the skeletal structures and the interactive ball and stick models were ‘new’ ways of representation. Furthermore, the results of Study Three showed that most participants described the structures that show all atoms explicitly (hydrogens included as a part of the structure) as being the most familiar to them. The representations employed in the original tutorial design did not match the representations most preferred by the participants, which might have caused the problems when dealing with more complex molecules. The more familiar representations were added to the adaptive feedback (see CD-ROM Stereochemistry Tutorial).

Exercise Two. The order of the task exploring structural isomers (Q2a) and the task exploring stereoisomers (Q2b) was changed for three reasons.

- The task related to stereoisomers (Q2b) involves different chunking to the task related to structural isomers (Q2a), with multiple representations but does not require the participants to make multiple comparisons (less conceptual demands) and is not loaded with as many molecules as the task related to the structural isomers. Therefore, if solved prior to the task involving structural isomers, it might help in preparing the participants for the next, more demanding task.
- The task related to stereoisomers (Q2b) was one of the solutions that were

offered in solving structural isomers (Q2a).

- In solving the problem of structural isomers of terpene molecules (Q2a) in Study Two, in their first attempt the participants clicked at the solution ‘1 and 4’, which was the solution for stereoisomers (Q2b) in the task that followed.

Therefore, if the task involving stereoisomers is solved prior to the task involving structural isomers one of the possible solutions (that was offered) can be eliminated by the simple recall of the previous task. This single change over could prepare the students for dealing with the conceptual demands in the task involving structural isomers and help them in reaching the solution for structural isomers. Figure 9.1. shows the two tasks of Exercise Two changed in order – now Question Two a) is addressing stereoisomers and Question Two b) is addressing structural isomers.

Introductory page to Exercise Three. In the tasks in Exercise Three the students explored the stereochemistry of the prostaglandin molecule. In order to help the students in finding the solutions for the tasks involving this complex molecule the hints were designed for each task. These were just a click away from providing a useful prompt in reaching a solution and were available to the students at the time they were solving each task problem. The introductory page to Exercise Three was to instruct the students how to use the hints available in exploring the stereochemistry of the prostaglandin molecule. De Jong and Van Joolingen (1998) described the use of hints in computer-based applications as a support in making predictions and promoting the learner’s discovery process with computer simulations. However, the effectiveness of any kind of instruction may be judged as it is received or understood by its users. The findings of Study Two showed that many of the participants in Study Two had not understood the intention of the introductory page prior to Exercise Three (see Table 7.12. in Study Two – Chapter 7) indicating that the intended student-software interaction has not been achieved. In order to give a clear message to students of the availability and the use of hints, the introductory page prior to Exercise Three was slightly amended; some words were changed and reordered. Figure 9.2. shows the changes made to the introductory page to Exercise Three.

In addition to the revision of the introductory page, in the amended adaptive feedback students are also reminded of the availability of the hints.

Question Two: Structures of Terpenes

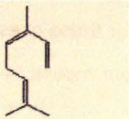
a) Click the structural formula on the right that is a stereoisomer of limonene.

Limonene

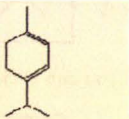


MDL

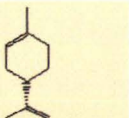
1



2



3



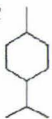
b) Which pairs of molecules would be best described as structural isomers?

1



MDL

2



MDL

3



MDL

4



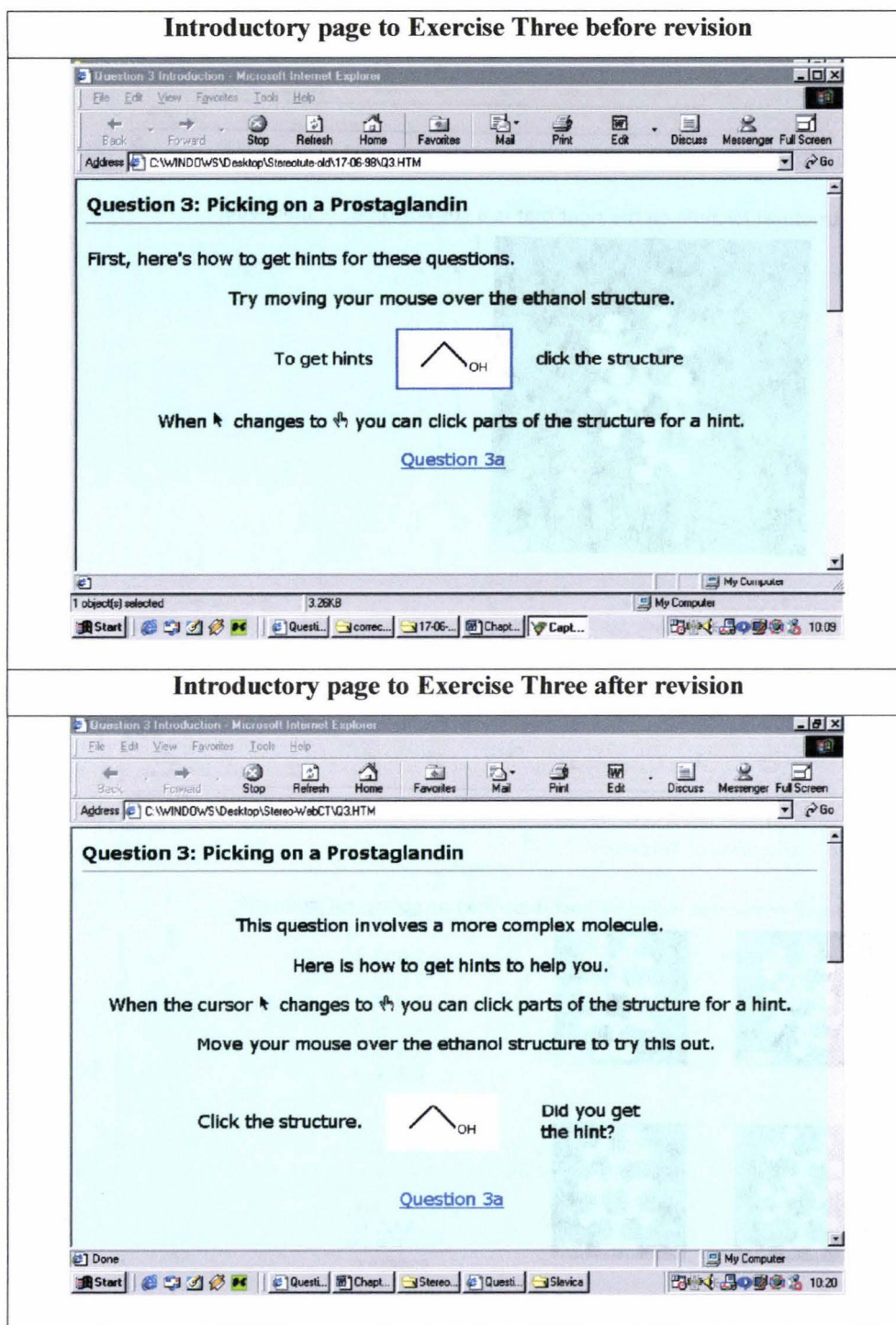
MDL

1 and 2
1 and 3
1 and 4
2 and 3
2 and 4
3 and 4

Remember that you can move the ball and stick models by clicking and dragging on

Stereochemistry Tutorial, 2000

Figure 9.1. The questions in Exercise Two exploring – a) stereoisomers and b) structural isomers.



Above, Stereochemistry Tutorial 1998; Below Stereochemistry Tutorial, 2000

Figure 9.2. The introductory page to Exercise Three before and after the revision.

The summary of the amendments made for each different exercise in the tutorial is given in Table 9.1.

Table 9.1. The summary of the minor amendments in the tutorial.

Exercise	Problems	Original design	Revision
One	No problems	Simple C4 alcohols Tasks: One way of representing molecules, either skeletal structures or ball and stick model Feedback: The same as in the tasks	Feedback: Two ways of representing molecules involved both the skeletal structures and the ball and stick models
Two	Q2a (structural isomers) - problems in counting atoms using both the skeletal structures and b&s models	Complex terpene molecules Tasks: From two ways of representing molecules, the skeletal structures and ball and stick model next to each other (Q2a, Q2b, Q2c) to skeletal structures only (Q2d, Q2e) Feedback: The same as in the tasks	Feedback: The more familiar representations (condensed structural formulae with hydrogens shown) were added. Tasks - Swap of Q2a and Q2b: Q2b contributes to Q2a. Changing the order of the two tasks could help in dealing with problem involving structural isomers of terpenes.
Three	Introductory page- the message was not understood Use of hints – some did not realise that hints were available Feedback Q3b – not helpful, too obvious (e.g. answer 3 - more than, tells the answer)	Prostaglandin molecule Tasks: Only skeletal structure was available. Hints: Hints were available to help students when dealing with the tasks Feedback: Skeletal structure was available, but the red colour was used to highlight the solution (numbers for rotation of single bonds; stereocentre-carbon atoms).	Introductory page- the instruction is rewritten, with slightly different order of words that inform about the availability and the use of hints Tasks: The ball and stick model was added. Feedback: The ball and stick model was added in the feedback, the use of hints was emphasised. For all tasks the feedback was checked so the responses are not too obvious.
All	Some students did not realise that glossary was available.	The link to glossary was not working from each task page and from each feedback page.	All links to glossary were checked. The button click links were provided from both, each task page and each feedback page (instead of the underlined word link that was available from some feedback pages).

Paytanic, 2000

9.1.2. Major Amendment - Exercise Four

The major amendment to the computer-based stereochemistry tutorial was an experiment aimed at addressing an issue raised in Study Three that was not present in the design of the original tutorial.

An additional Exercise Four was added to the tutorial and can be viewed in the CD ROM Stereochemistry Tutorial. When compared to the design of the original tutorial,

the added Exercise Four involved two changes.

- The change in the objective - the objective selected to be explored was the property of enantiomers. Therefore, the added Exercise Four addressed the macroscopic property of stereoisomers.
- The change in the way the tasks were designed – in this exercise guided discovery was employed. An animation, which does/does not show the rotation of the plane of polarised light, has been developed and inserted in Exercise Four and in the glossary. This amendment involved a change in the response to a student's answer that involved a simulation of the measurement of the predicted property and allowed the students to directly observe whether their answer was correct or not.

Although discovery learning methods after being introduced with enthusiasm and high expectations in the 1960s were later criticised as problematic (Hodson, 1993), the alternatives in a form of theory-driven or guided approaches were described as theoretically valid and pedagogically effective learning experiences that provide a learner with an opportunity to conduct scientific investigation and develop both the conceptual knowledge and procedural knowledge. Alternatives such as POE tasks (Kearney & Treagust, 1999) or expert guided scientific discovery employed in computer-based simulations (De Jong & Van Joolingen, 1998) are described to provide activities that enable the teacher to tailor the learning experiences precisely to the teaching/learning goals and to eliminate the *noise* of many laboratory activities that interfere with learning.

Both aspects of Exercise Four mentioned above are elaborated below.

(i) The Need to Address Properties – The Macroscopic Dimension

Several insights from Study Three (Chapter 8) were considered in designing Exercise Four.

- The results suggested that students experience chemistry in two different worlds. One is the world in which chemistry is taught to them based upon the abstract chemistry concepts (micro-symbolic according to Johnstone (1991) or students' dream world according to Study Three), the other is the world of real chemistry (macro according to Johnstone or students' real world according to Study Three),

that, as described by the participants in Study Three, mainly exists somewhere else, in places such as chemistry laboratories. The two worlds of chemistry seemed to be separated from each other.

- The results of the ways in which students conceptualise enantiomers revealed that students recalled the optical activity of enantiomers, a macroscopic, physical property highlighted in a definition of enantiomers, and used that description to distinguish this kind of isomers from others.

In order to decrease the gap between the two worlds of stereochemistry, it appeared reasonable to target the optical activity of enantiomers as this property was the one with which some students showed familiarity (although with the use of words for it only). It was hoped that the emphasis on this property, but in a different way, could initiate the awareness of properties of other types of stereoisomers, and also of properties other than the optical activity.

(a) Computers versus Laboratory Experiments

Laboratory classes, as a main teaching method for teaching chemistry, were introduced in Chapter 3 (section 3.2.3.). Also, a debate of the value of practical laboratories for teaching science was introduced in previous Study Three, Chapter 8, in which the difficulties the students face in learning and connecting the practical, experimental skills to the theoretical conceptual knowledge of chemistry are recognised as well (Draper, 1998; Hodson, 1993; Johnstone, 1999; Solomon, 1988).

Students' responses in Study Three, in which the sight of colourless liquid was associated with laboratory classes suggest that quite often students perform a laboratory experiment as an isolated part of the course, following the procedure, observing what happens and recording only the results they were asked for. Johnstone (1999) and Draper (1998) commented that sometimes very little connection is made between the practical observations or measurements and the theoretical background. Although individual practical work is emphasised in teaching high school chemistry in New Zealand there is always a number of students who enter university with very little, or no, practical experience.

Usually laboratory experiments do not cover all chemistry topics introduced at the lectures. Furthermore, laboratory classes do not always follow the theoretical instruction

given in class, and sometimes there is a mismatch in timetable between the two. Also lectures and laboratory classes run in separate areas (laboratory and lecture theatre), like isolated units, with no connections.

The computer work can provide a very valuable addition to an existing practice. Bowen (1998) described how the use of computers opens up the possibility of integrating the symbolic, micro and macro nature of chemistry. By the use of computers, macroscopic measurements can be integrated into the abstract, symbolic or microscopic aspects of chemical phenomena.

Yaron, Freeland, Lange, and Milton (2000) claimed that computer-based instruction can be used as a support in chemistry to address some of the teaching/learning difficulties and described how simulations relate concepts to meaningful and motivating contexts, make the concepts more concrete and visual, and promote active learning. The authors highlighted how the design of the software should draw on teaching and learning research. According to Yaron et al., in order to improve students' conceptual understanding teachers must substantially change how students interact with the material and better facilitate their exploration of relationships between abstract theoretical concepts and observable chemical processes.

As a result of Study Three, and in the line with the discussion by Yaron et al., it was decided to explore whether a new approach in the design of Exercise Four could be usefully taken to help the macro-micro problem.

The aim of Exercise Four and the inserted animation was not to replace a 'hands on' experiment in which students learn practical skills (how to fill up the polarimeter tube with a sample or to read the rotation from the observer's knob). Rather, the aim was to connect the observable property with a molecular structure, in a way which differs from that achievable by performing the real experiment.

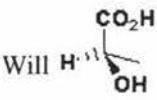
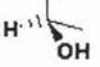
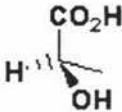
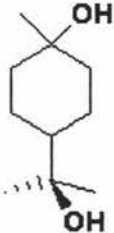
(ii) Design of Exercise Four

Exercise Four is designed in the form of exploration, but supported by a conceptual explanation using the abstract (symbolic and micro) nature that is available through the Help/Explanation link. An approach employed in Exercise Four is in the line of learning by discovery or guided discovery and involves the activities that are listed by Shrager and Langley (1990) as important activities that constitute the process of scientific

discovery.

The summary of the design features employed in Exercise Four is given in Table 9.2. Each feature of the design is described separately.

Table 9.2. Design features employed in designing Exercise Four.

Design features	Example
POE design (Kearney and Treagust, 1999)	Prediction  Will  rotate polarised light? Choose an answer and observe what happens. <u>Yes</u> <u>No</u>
Animation (Yaron et al., 2000)	Observation  <u>Explanation</u> <u>Next</u> <i>Back</i>
The model progression (De Yong and van Joolingen, 1998)	Task 1  Task 2 

Stereochemistry Tutorial, 2000

(a) *Predict-Observe-Explain (POE) Tasks*

An approach employed in the design of Exercise Four involves ‘predict - observe - conclude on your own’ design, which is similar to POE (Predict-Observe-Explain) task design employed in the study by Kearney and Treagust (1999). Kearney and Treagust (1999) stated that a computer environment has the potential to be an ideal support for the sequencing and presentation of POE tasks. POE tasks are in the line of the constructivism theory of learning and the authors believe that the computer environment has the potential to encourage social interaction and discussion, as well as personal reflections which are so important in the constructivist classroom.

This exploratory type of exercise asks the student to predict the optical activity of the compound under investigation from a given structure (task question). Then, the student observes what happens through the given animation in which the property is measured, and is left on his/her own to conclude if his/her prediction is right or wrong. If needed, the student is given the opportunity to test or check his/her own reasoning, with the formal explanation given in a link "Explanation" (formerly called Help). Therefore, the task design in Exercise Four has changed in the sense of not providing feedback with confirmatory statements such as "You are right" or "No, these two are not .. because ..", that were present in the other three exercises. Finally, the students were expected to interpret the results of the animated experiment in terms of the abstract, symbolic representation of a molecule.

During the stimulated recall interviews, the steps of the procedure were replayed to the student (with both the prediction and observation). The last step of interpretation of the results was checked when the students were interviewed and gave verbal explanations for the observed phenomena (for groups was also found in student-student discussion). This kind of the task design fits into the description of the POE tasks (Kearney & Treagust, 1999).

Exercise Four can be seen on CD-ROM Stereochemistry Tutorial.

(b) Why Animation?

Animations in Exercise Four, that simulate the measurements of the macroscopic property of enantiomers, were intended to be used as an effective tool to enable students to relate the symbolic representation of enantiomers to the observable property of the rotation of the plane polarised light.

The on-line conference Summer 2000 CONFCHEM (May 12 - June 6, 2000), entitled The Use of Computer Simulations in General Chemistry, addressed the use of technology in teaching and learning chemistry, with the accent on animations and simulations. Chemistry educators who are using computers in their teaching shared their experiences in the form of submitted papers and became involved in a rich discussion. The simple descriptions of animations and simulations and the difference between them is given by Chieh and Sze (2000, Abstract, para. 1):

Animations show step-wise sequences of diagrams, numbers, or images to illustrate complicated concepts or theories. Simulations, on the other hand, are

imitations of systems for users. The user enters or alters certain parameters, and the computer will reveal the consequences or changes. Some random or uncertain elements are involved in simulations. Experiments using real systems are the best way to explore science, and simulations offer students alternative ways to discover when real systems are not available or impossible to set-up.

According to Reeves (2000) animations are often used to illustrate the models of how phenomena occur at the atomic and molecular level. Answering the question: "What characterizes an effective animation or video?" (Introduction, para. 3), Reeves discussed that like "any teaching tool, an animation or video must be sharply focussed on the message the instructor is illustrating" and for this reason, these media should be reasonably short in duration. Reeves described them as "particularly effective tools for illustrating the macroscopic, microscopic, symbolic relationship by providing concrete views of the same process" from each of the different perspectives (Session A discussion archive, Date: Mon, 15 May 2000 09:52:22 -0400, para. 2).

The aim of the design of animation in Exercise Four fits this description by Reeves (2000). The animation addresses one single aspect of stereochemical phenomena repeated for different chemical compounds. It is sharply focussed on the message the researcher is illustrating and is short in duration.

The computer animation, similar to the one developed for Study Four, showing how the polarimeter does/does not rotate the plane of polarised light, has been used in teaching stereochemistry and can be found in the chemistry department's web tutorials of many universities. The animation found at:

<http://www.colby.edu/chemistry/OCHEM/DEMOS/Chirality.html>, was adapted by the researcher. Students do not perform such measurements during the regular laboratory classes, so the developed animation could back up the lecture demonstration and be shown in a lecture as well.

An animation was used to overcome the separation between the student real world of chemistry and the abstract, dream world of chemistry (see Study Three). Pankuch (2000) described how the use of animation is particularly suitable for combining topics that are usually covered separately and clarifying their relationships.

Discussing the use of multimedia methods to achieve long lasting effects (rather than just the short term Hawthorne effect), Pankuch highlighted that the media should not be used for what you are doing successfully already with traditional ways of teaching.

Indeed, animations cannot be given on the pages of a textbook or be written on the blackboard during a lecture, but they can be performed using computers. With the increasing use of computers and multimedia in teaching and learning their appropriate use becomes more and more sensitive. According to the meta-analysis of the efficacy of CAI by Fletcher-Flinn and Gravatt (1995) and the results they obtained on the effect size with respect to educational level, the pattern of moderate results “may reflect a decline in novelty as computers become more commonplace in school and at home” (p. 227).

According to Pankuch, the use of animations and simulations has the potential of being more efficient and effective ways of getting students to form “useful mental models” (para. 1). Justifying the use of animation Pankuch says: “Some of the increased learning is undoubtedly due to increased time spent on the combined material, but some is also likely due to the fact that the animations are new and interactive” (How effective is it?, para. 5). The repetition of the same ideas in slightly different ways by the play of similar, but slightly different animations (depending on the compound being investigated) can be used for deepening understanding (Pankuch, 2000).

Finally, the tutorial development with the added animation meets the criteria for a Laurillardian Guided-Discovery Learning Environment or Laurillard model of learning with multimedia (Laurillard, 1994). According to Laurillard, a framework for analysing educational media of the teaching-learning process in a multimedia environment consists essentially of:

- **Discussion** between teacher and learner at the level of descriptions;
- **Interaction** between the learner and some special aspects of the world defined by the teacher;
- **Adaptation** of the world by the teacher and action by the learner;
- **Reflection** on the learner’s performance by both teacher and learner.

Laurillard described how the modes of learning that involve adaptation and reflection are the vital aspects of learning that link the experiential to the conceptual learning in contrast to traditional modes of teaching which favoured delivery of the teacher’s descriptions. Guided discovery learning is a mode that provides both adaptation and reflection, and according to Laurillard the ‘multimedia tutorial simulations’ are the only

form of instructions in which the use of technology can meet most of the technological and pedagogical requirements of multimedia learning.

It can be argued that the development of Stereochemistry Tutorial had all the steps listed above. The first two steps were part of the studies described earlier. Studies One, Two and Three involved discussion between the researcher and learner, but also student interaction with a software which was a world defined by the teacher or software designers (Study One and Study Two respectively). The last two steps, adaptation and reflection, are part of the present study.

(c) The Model Progression

As in the reminder of the tutorial, in the design of Exercise Four a progression model was involved. The model progression was structured by using more complex molecules in Question Two (Exercise Two) compared to the simple molecules in the tasks of Question One (Exercise One). When the model (molecule of organic compound) increased in complexity the students were able to apply the knowledge gained in solving problems with simple molecules. De Jong and Van Joolingen (1998) found the model progression to be successful in enlarging the students' intuitive knowledge and supporting the learning processes.

In conclusion, the design employed in Exercise Four is an application of the constructivism and guided discovery (Windschitl & Andre, 1998).

Although addressing questions relating to scientific discovery learning with computer simulations of conceptual domains, the forms of the support discussed by De Jong and Van Joolingen (1998) can be applied to diverse types of software design, and were considered in the design of Exercise Four using animation.

First, each task in Exercise Four started with a question that involved students making a prediction (hypothesis) and testing it in the next step. De Jong and Van Joolingen argue that having questions to guide the learner through the discovery process is a dimension in the planning of support for hypothesis generation.

Second, each task in Exercise Four required students to use a system of elimination to arrive at a solution. De Jong and Van Joolingen (1998) describe how support for hypothesis generation in scientific discovery could be realised by the option in which the learners are given an opportunity to employ a strategy of elimination.

Third, a model progression was employed as a support for the learning process (De Jong & Van Joolingen, 1998). Moving through Exercise Four students were engaged with the increasingly complex molecules.

Fourth, the Help (Explanation) link, that was available in all tasks in Exercise Four, enabled students to reach the permanently available formal or 'expert' information. De Jong and Van Joolingen (1998) described that only the information available at the appropriate moment can confront learners' prior knowledge and stimulate their conceptual development.

Finally in order to avoid cognitive overload (see Johnstone, 1997), chunking with no multiple perspectives was used in the design of Exercise Four. Gruber et al. (as cited in De Jong & Van Joolingen, 1998) warn that some instructional measures may raise cognitive overload by introducing more complexity (or multiple perspectives) into the environment.

9.2. STUDENT USE OF THE REVISED TUTORIAL

9.2.1. Research Questions

The main Research Question 4:

How do students interact with an in-house authored, chemical concept-centred computer-based tutorial, amended to take account of student prior knowledge and approach to learning?

that was set up and given in Chapter 4, section 4.4. is addressed in Study Four. This main research question was further refined into a series of questions. To provide the focus for this study, the research questions were formulated after the tutorial was amended according to the findings of Study Two and Study Three respectively. Both the minor and major amendments were addressed by the research questions; particular attention was given to the major amendment in the tutorial by the addition of Exercise Four. The research questions focussed on the particular targets, i.e. usefulness of the amendments that had been made in the tutorial.

4 a) How do students experience the amended computer-based stereochemistry tutorial? With respect to the:

- (i) Amendments in the adaptive feedback done in Exercise Two, in which the more familiar structural formulae with the hydrogens included were added for more complex terpene molecules;
- (ii) Understanding of the introductory page to Exercise Three and the use of the hints available in Exercise Three;
- (iii) The use of glossary?

4 b) How do students experience the added Exercise Four that was developed on the basis of results from Study Three? With respect to:

- (i) The design of Exercise Four, compared to the design of the rest of tutorial (Exercise One - Exercise Three);
- (ii) Exploring the property of enantiomers;
- (iii) Exploring properties, other than the one explored in the tutorial and of the stereoisomers other than enantiomers (e.g. *cis-trans* isomers)?

9.3. SETTING OF THE STUDY

9.3.1. Students and Sampling

In Study Four, which was the final part of the thesis, initially it was planned to perform in-depth interviews with half a dozen students, preferably an equal number of males and females. After the lecture at which the stereochemistry unit was introduced, the researcher visited a lecture class, introduced herself and the study and asked for volunteers. Students were given a written invitation sheet and those willing to participate filled in the sheets stating the time they were available for participation. The researcher phoned students individually to make appointments. Fourteen volunteers applied and all of them participated resulting, however, in an unbalanced participant gender profile. Although five females worked as groups (one of three, one of two), all students were individually interviewed.

The profile of participants who volunteered in Study Four is given in Table 9.3.

Table 9.3. Profile of the participants in Study Four.

Criteria/variables		Student proportion	
		Number	%
Gender	Females (F)	9	64
	Males (M)	5	36
Chemistry Background*	Form 7 and Bursary	9	64
	Form 6 and Form 5 [#]	5	36

* Form 7 - final year of high school (17-18 years old), but one participant was 14 years old

[#] Two F and two M finished high school three or more years previously.

9.3.2. Techniques in Data Collection

The same technique of stimulated recall interviewing, accompanied with videotape observations and the use of observational sheets (just an additional Exercise Four was added to the sheet) as described earlier in Study Two was used in this study. The data administration was similar to that described in Study Two.

9.3.3. Data Analysis

Step 1 – Minor amendments

The evaluation of the effectiveness of the minor amendments related to the Research Question 4a. This part of the analysis strongly focussed on the tutorial design with respect to the aspects listed in the research question (i) – (iii) that failed to provide the instruction intended by the initial design and were identified as those which affected student-software interaction and student achievement of intended learning outcomes in Study Two.

Additional more familiar representations were added in the adaptive feedback of Exercise Two (terpene molecules). Particular attention was given to the task of exploring structural isomers, as in Study Two the participants experienced most difficulties with that task. In addition, the order of the tasks was changed so the task exploring stereoisomers preceded that exploring structural isomers.

The effectiveness of the amended introductory page was evaluated to discover if, and

how often, the participants used the hints available in the tasks of Exercise Three.

Finally the evaluation of the navigation to the glossary was also evaluated to discover if, and how often, the participants navigated to the glossary while progressing through the tutorial.

All these aspects were analysed by monitoring the student progress through the first three exercises, using the observational sheets, watching the tapes and checking the student verbal responses. The procedure was the same as described in Step 3 of the analysis employed in Study Two (Chapter 7).

Step 2 – Major amendment

In order to answer the Research Question 4b and to test the effectiveness of the major amendment (the added Exercise Four), the analysis procedure of the individual sets of the related data followed that described in Study Two (Chapter 7), particularly steps 1 and 2.

The analysis was focussed to answer the questions (i) – (iii) of the Research Question 4b.

9.4. RESULTS

As the two aspects of the amendments were introduced and described, one related to the improvements of the already designed tutorial (minor) and the Research Question 4a, the other related to the newly added exercise (major) and the Research Question 4b. The results are given in order to reflect these two aspects.

9.4.1. Responses to Amended Tasks: Exercise One - Exercise Three

The summary of the results related to the Research Question 4a is given in Table 9.4.

Table 9.4. The summary of the results related to the Research Question 4 a).

Student's experience of the amended computer-based stereochemistry tutorial	Evaluation	Results
(i) Amendments in the adaptive feedback in Exercise Two, in which the more familiar structural formulae with the hydrogens included were added for more complex terpene molecules	Student progress through the tutorial, from Exercises One to Exercise Three informed of the effectiveness of all minor amendments. Particular attention was given to the task related to structural isomers in Exercise Two (the influence of both the added more familiar representation in a adaptive feedback and the change in the order of the tasks).	Students found it easy dealing with simple molecules but faced difficulties in problems with increased complex molecules – similar pattern as observed before the amendments were made. The change in order of two Exercise Two tasks did not strongly influence student decisions in solving problem of structural isomers of terpenes, still the most participants in their first attempt clicked at the solution 1&4, the same they had completed previously.
(ii) Understanding of the introductory page to Exercise Three and the use of the hints available in Exercise Three	Student interaction with Exercise Three and the use of hints.	All participants who performed Exercise Three used hints.
(iii) The use of glossary	Navigation to glossary from all tasks in the tutorial.	More frequent visits to glossary compared to the findings in Study Two.

Pavlinic, 2000

(i) The increased effectiveness, if any, of the slightly amended tasks (from Exercise One to Exercise Three) were tested by monitoring student progress and success in solving stereochemical problems versus the complexity of the molecules employed when moving through the tutorial. The same question was addressed in Study Two, therefore the results of two studies can be compared.

Out of fourteen participants, nine students worked singly, while the rest formed two groups, one pair and the one of three, resulting in eleven observational sheets being analysed. Table 9.5. shows the summary of analysed observational sheets (interactive maps), supported by the evidence in the recorded tapes and interview transcripts, and gives the participants' progression/success per stereochemistry concept with increasing level of the complexity of the molecules that was employed when moving from

Exercise One to Exercise Three. The results are discussed later in section (i) Discussion.

Table 9.5. The student/group progress through amended tutorial recorded as a number of attempts used to reach a correct solution per type of stereochemical concept tested.

Concept / Isomerism being investigated		No of Students/No of attempts to solve a problem								
		Exercise One (C4-Alcohols)			Exercise Two (Terpenes)			Exercise Three* (Prostaglandin)		
		1 st	2 nd	>2	1 st	2 nd	>2	1 st	2 nd	>2
Structural Isomers	ball & stick	9	2	0	1	6	4			
	skeletal	11	0	0						
Enantiomers	ball & stick	9	2	0						
	skeletal				5	6	0			
Stereocentre		7	3	1				6	2	2
Conformational Isomers	ball & stick	4	7	0						
	skeletal							4	3	2
Diastereomers	double bond				5	2	4	5	3	1
	ring plane							1	8 [#]	
Stereoisomers					8	2	1			
Configurational					5	6	0			

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*One student has not done Exercise Three, the other done only Q3a

[#] Only two options were available

(ii) The videotape evidence and records written in observational sheets indicated that all the participants in this study who did Exercise Three used the hints available. In addition, during the interviews none of the participants showed that any misinterpretation of the instruction in the amended introductory page to Exercise Three had occurred. Therefore, the data suggested that the participants understood the rewritten instruction given in the amended introductory page to Exercise Three. Out of fourteen participants, one student did not do Exercise Three. After spending forty minutes on the tutorial and finishing Exercise Two, the student was asked to miss Exercise Three and go straight to Exercise Four. Of the participants that used the hints, four of them just used them in the first task of Exercise Three (exploring the number of stereocentres).

(iii) The glossary was visited by all but one pair of students.

In addition, the themes that influenced and contributed to student-software interaction that were earlier discovered in Study Two were relevant and are confirmed repeatedly in Study Four. The general satisfaction with the tutorial and with the multiple ways of representing molecules, with the feedback, the navigation to the glossary and the use of hints, were all clearly expressed. Apart from discussing the representations preferred for different isomer types, these participants also indicated problems with interpreting the skeletal structures or the counting of atoms using the ball and stick models when dealing with complex molecules. Comments relating to the use of multiple representations/models and the students' ability to switch from one representation/model to the other at a time of instruction or task performance were found similar to those identified in Study Two for the task exploring stereoisomers in Exercise Two (the task is shown in Figure 9.1. a).

Some participants, such as Rebi, described having no difficulties in dealing with both representations and switching to and from the skeletal structures to the ball and stick models.

Rebi: I don't have any trouble with skeletal formulae because at the tutorial you have to do with it and transfer it to ball and stick model and do other things .. yeah

R: So you transfer it in your mind?

Rebi: Yeah, yeah, It's very easy to understand, I don't have any problems with that.

However, to others problems of transition from one representation/model to another were experienced. A comment similar to the one identified for the same task in Study Two was made by another participant in this study:

Ray: At first, I thought that the structure we've got up there ... like .. the one in the corner, these ones need different ball and stick models, and so I was wondering if you could put the ball and stick models so you could look at them and they could help, but you get them when you get wrong, [feedback for Q2a – in Study Four the ball and stick models were added in the feedback] ..

R: In the feedback you were given both ..

Ray: Yeah, that was good .., yeah reinforce the understanding here

These comments about Exercise Two suggest that, to some students, difficulties in transition from one representation/model to another were still present even after practising them in Exercise One. This suggests that to some students in a classroom confusion might be present whenever a teacher switches from one representation to another during instruction. Teachers should continue to use multiple representations, but

in a class of students with a range of chemistry backgrounds, care should be taken when and how to use the multiple representations. Also, when teachers shift from one representation to another, they should make sure that the students understand all the representations used and why the shifts were made.

No different student responses or additional themes were identified for the first three exercises.

The effectiveness of the minor amendments was checked through the evaluation of student achievement of intended learning outcomes, the same task objectives that were selected and tested in Study Two. The results obtained in this study are given in Table 9.6. and refer to the responses from Exercise One – Exercise Three.

Table 9.6. Student achievement of intended learning outcomes (Exercise One – Exercise Three) in Study Four.

Task Objectives	Achievement /No. of students		
	Achieved	Not achieved	No clear data
• Describe structural isomers	10	4	-
• Describe stereoisomers	11	2	1
• Describe the difference between stereoisomers and structural isomers	1	9	4
• Describe conformational isomers	8	2	4
• Describe the difference between conformational and configurational isomers	5	7	2
• Define chirality and recognise the presence of stereocentres in molecules	8	3	3
• Define enantiomers	12	-	2
• Define diastereomers	8	4	2
• Explain the difference between enantiomers and diastereomers	8	3	3
Total number of student understandings of each of the objectives	71	34	21

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The numbers obtained in Table 9.6. show that the achievement was obtained by more than half the participants for seven of the nine task objectives. Out of the total number of evaluated responses, 56.3 % were evaluated as achieved, a similar performance to Study Two.

Again most difficulty was found in the achievement of more challenging objectives such as describing the difference between structural isomers and stereoisomers or describing the difference between conformational and configurational isomers.

(i) Discussion

(a) *Effectiveness of the Minor Amendments*

When the results given in Table 9.5. are compared with the results obtained in Study Two (see Chapter 7, Table 7.9.), a similar pattern in student success per concept is found. However, the comparisons are indicative rather than quantitatively determined because the student group interviewed and other learning opportunities were not controlled.

In both Study Two and Study Four the interviews were carried out after the participants were exposed to the concepts at lectures. The dates of the student participation in Study Two were 18/03/98 for four participants, 20/05/98 for six participants and 27/05/98 for one participant (therefore the last seven participants had an opportunity to do a revision before the mid-semester test). In Study Four, the interviews were held from 24/03/00 to 12/04/00. When the results obtained for Exercise One (simple problems, C-4 alcohols) in the two tables were compared in more detail, it was found that the results indicating more than two attempts at solving the problems differed for the concepts of structural isomers, enantiomers and diastereomers. The zeros in Table 9.5. for this category obtained in this study indicate the possible influence of the amendments done on tasks. After the first failed attempt, when dealing with simple molecules the amended and the more appropriate feedback enabled the students to solve the problems.

However, when the results in Table 7.9. in Study Two and in Table 9.5. of this study are compared for the tasks involving more complex molecules, it appears that the minor amendments did not influence the pattern of the student-tasks interactive maps when dealing with these molecules (Exercise Two and Exercise Three).

The task involving the concept of structural isomers in Exercise Two appeared to remain the most problematic task, although the more familiar representations were added in the feedback and a change in the order of the tasks for structural isomers and stereoisomers was made. Only one participant solved this problem in her first attempt. The change in order of the two tasks in Exercise Two did not strongly influence student decisions in solving structural isomers; still most of the participants (13 of 14) in their first attempt clicked at solution '1 and 4', the solution discovered immediately previously at the completed stereoisomers task. The results suggest that the students were mostly concentrated on one particular task at a time and that very little connection

between the tasks was made. The student response to this task was one of the criteria in evaluation of the achievement for the task objective – the difference between the structural isomers and stereoisomers. The results for this task objective significantly contributed to the responses evaluated as not achieved (9 of 34).

It might be that, apart from the amendments in the feedback and in the tasks order, redesign of this particular task (structural isomers of terpenes) and better chunking should be attempted to avoid overloading the page (that was also identified in Study Two).

When dealing with prostaglandin molecule (Exercise Three) in this study, all participants who reached the introductory page to Exercise Three ‘got’ the message and used the hints available in the tasks. However, from the nine students who used hints in the first task (Q3a), the number dropped to three in the next task (Q3b), two in Q3c and only one in Q3d. From those who used hints in the first task, four students did not use hints for the rest of the tasks in Exercise Three. For different reasons (e.g. some students described that in task one the instruction was still fresh from the introductory page but was later forgotten, and others wanted to solve the rest of the tasks on their own and with no help), the numbers of students who successfully reached the answer before and after the revision of the tutorial differed only slightly for the concept of stereocentre that was explored in the first task of Exercise Three in which the hints were used by the most participants.

In Study Two, only a few students (one pair and one single student) completed the task exploring diastereomers or *cis-trans* isomers about a ring plane (the tutorial was still in the development phase and the task was added later) and not enough data were collected for analysis. However, the results obtained in this study show how confusion about a ‘very familiar’ type of isomerism arose, when the problem was moved from an understanding limited to only *cis-trans* isomers about a double bond, to an understanding of the same type of isomerism about a ring plane. Most of the participants failed to solve the problem at their first attempt.

One reason for the observed outcomes could be that familiarity with a certain type of isomerism in a simple molecule does not necessarily correspond with a deeper understanding of that type of isomerism. The results of Study Three, which described the students’ awareness of *cis-trans* isomers indicated that, although familiar with this type of isomerism in the simplest molecule, students were still confused with terms. The

interviews in this study confirmed that there are still students not familiar with this type of isomerism. For example Jolly described:

I am still confused with *cis* and *trans* because I haven't done Bursary .. everyone seems to know about it and just go through [hand movement] skip over .. and I don't .. I mean when they asked if everybody knows what *cis-trans* is and everybody went YEEEEES and I said NOOOO .., I was the only people who said NOOOO and knew nothing about it.

The other example is the explanation given by Kate for a concept of stereocentre in Exercise Three: “ .. like, the stereocentre, I get them, I just not having to find them in a big structure”. Stereocentre is a concept that most participants did not describe as difficult to deal with.

Another aspect could be assigned to the limited instruction given by a teacher or lecturer to students when introducing the concepts. The instruction given to students should provide a wider range of examples. At high school level students are introduced to *cis-trans* isomers mostly with examples involving simple structures containing double bonds. The use of examples that are limited to the compounds containing double bonds only in instruction might be the cause of students' limited awareness of this type of isomerism. A very important insight that comes out clearly here is the use of the tutorial which introduced the different aspect of this type of isomerism. The tutorial feedback was found very useful in providing the students with the opportunity to construct knowledge from the information given when their respective backgrounds were very different.

(b) *Effectiveness of Model Progression*

Student progress versus complexity of the molecules used in tasks or the relationship between student success in solving stereochemistry concepts and the complexity of the molecules showed that student ability to confidently solve problems decreased with the increase of complexity of molecules. Student progress was measured by monitoring the number of attempts per concept employed in each task to reach the correct solution, from Exercise One to Exercise Three.

To introduce new concepts or demonstrate laws or principles in chemistry, teachers, lecturers or textbook writers, almost without exception at high school level and generally at lower university level, use simple molecules. In order to make new

concepts more understandable to students, it is reasonable to use molecules that are easier to conceptualise for students. Quite often the models and examples given in a lecture are the same as those written in the recommended textbook. Once one lecture topic is over, a new one takes its place in an ongoing process. Then, in a test or an exam the students often have to apply the concept to more complex molecules. It is assumed that if they 'know the concept they should be able to apply it, regardless of the type of the molecules being used'. It is assumed that students can switch from the simple problems previously shown and solved in the lecture, to problems involving more complex molecules, in the same way the lecturer does. This study showed that quite often that was not the case, indicating a gap between the way students (novices) and the way teachers (experts) are able to deal with a concept. According to Lemke (1994; 2002) the confidence in dealing with the problems involving complex concepts and complex molecules is likely to come with experience, after many years spent with similar problems.

However, Lemke argues that the teachers must teach students about other examples or how to deal with them. That was the aim when students were challenged in the tutorial with the more complex molecules or when the stereochemical concepts were explored from the slightly different perspective than that commonly found in textbooks.

A diversity which sometimes does not fit a well-established pattern (for example, *cis-trans* isomers just about a double bond), such as that employed in the design of this tutorial provided the students with new practice situations, a variation that widened their experiences and made them more prepared to deal with new situations such as in exams. This is in accordance with the phenomenographical view of learning and teaching in which Marton and Booth (1997) argue that a major task of pedagogy is to identify the critical features and focus on them by building a 'relevance structure' and making the use of 'the architecture of variation'. If provided with a wider range of experiences of any particular type of isomerism, students' relevance structure when learning about isomerism could differ. Different student experiences of stereochemistry that derived from the different ways they are taught might result in different ways of applying something learned.

(c) *Student Achievement of Intended Learning Outcomes*

Finally, the effectiveness of the minor amendments is discussed through the evaluation

of student achievement of the task objectives that were selected and tested in Study Two.

The general pattern of the results obtained in this study (Table 9.6.) is similar to that obtained in Study Two (Chapter 7, Table 7.8.).

While the minor amendments improved the technical omissions and provided the students with the better student-software interaction (navigation, better feedback), the structure of the tutorial was retained with the same model progression with complex molecules in Exercise Two and Exercise Three, as originally designed. This study confirmed the findings in Study Two, suggesting that the important factor affecting the students' achievement of the concept-related objectives remained the complexity of the molecules. The added condensed structures in the feedback of Exercise Two only slightly improved student progress and therefore student achievement of intended learning outcomes.

The recommendation from this study is that educational research should target investigation into the use of examples of complex molecules to assist student understanding of chemistry concepts.

9.4.2. Responses to Exercise Four

At the beginning of the interview, students were asked to comment on the tutorial as a whole. In their very first response to the tutorial, a number of students, such as Rebi, recalled Exercise Four:

I sort of reinforced stuff in my mind from the lectures .. but I never related to think about it because I had never a visual for it .. like .. how to relate the polarised light, we were not related that at all, like all reading stuff .. yeah ..

The aim of Study Four (stated in the research questions of this study) was to discover how students experienced the added Exercise Four. This exercise differs because it addresses the property of enantiomers. Furthermore, the design of this exercise differs from the design being employed in the rest of tutorial.

These aspects are related to the Research Questions 4b and are described below.

(i) Design of Exercise Four

The analysis considered the students' responses (both affective and cognitive) to the

question: “How did you find this last exercise?” and the responses in which they articulated their opinion of the design of this exercise versus the design of the rest of the tutorial (Exercise One - Exercise Three). Three factors relating to the general description of the design were identified. An additional aspect, in which the students discussed the self-evaluation by observing the animation with no additional feedback, was analysed. Table 9.7. shows student responses to the design of Exercise Four, classified according to the different means of responding (both affective and cognitive).

Table 9.7. Students’ responses to the design of Exercise Four distributed to different means of responding.

Participant/ Pseudonym	Exercise Four versus Exercises One -Three			Feedback	
	Good/all right	This exercise was easier	More visual exercise	Confirmation – you are right	Observing animation and self- evaluation
1. Sue			✓		✓
2. May			✓		✓
3. Kate	✓	✓	✓		✓
4. Shy					✓
5. Ray	✓	✓	✓		✓
6. Ruth	✓	✓			✓
7. Rebi	✓		✓	✓	
8. Rose		✓			✓
9. Bert	✓				✓
10. James		✓			✓
11. Gavin	✓				✓
12. Josh	✓				✓
13. Alan	✓				✓
14. Jolly	✓				✓
Total	9	5	5	1	13

Pavlinic, 2000

When the task design changed from the pattern established in the first three exercises some students were surprised. Most of them welcomed this exercise, found it easy to follow, with a clear message, and not overloaded with respect to the number of chunks present on the page. Some of the participants distinguished the change in the design in their own description. From others the responses were collected after viewing the animation and when they were asked “Viewing the animation, was it enough for

confirming your answer/prediction? or “Did you need any other confirmation for your answer/prediction?”

Some students did not see a difference in task design between this task and the tasks given before, and only one participant wanted explicit confirmation of her choice.

A very few students passed through the tutorial without making any comments; the majority indicated that they had noticed a difference in the task design from Exercises One – Three and the one in Exercise Four.

Responses such as Alan’s: “Ah, polar .. this is good actually, the movie thing .. it was good” belong to this group **good-all right** and were collected from the majority of the participants (9 of 14 or 64 % as shown in Table 9.7.). Neither a detailed description of the exercise nor detailed explanations of why it was good were found in their descriptions.

The next group involves description by five different participants, saying how **this exercise is easier**. Students compared this exercise to other ones and tried to explain why this exercise seemed easier for them:

Oh, it could be better if we’d done it at the beginning.. I found that kind of one easy. The way the molecule is shown gives you, I mean a central carbon and different groups coming off, to see it straight away yes or no. (Ruth)

Ray: This one, the number four was quite good. [Exercise Four appeared on the tape] The first one, I didn’t realise the number one, I really didn’t understand some of the questions because it was quite hard and I did not like it, but this one was quite easy and very interesting..

R: In which way?

Ray: It was just cool having a simulator. You heard a little bit at the lectures, I understand that, but actually seeing it done, I mean I would never have a vision like that. .. Ah, as a whole, it was really good, I really liked that thing, it was really good to be able to see ..

It might be that this exercise was less demanding on students because the focus of the tasks was on the one aspect only, but it could be due to the effect of the animation. In addition, it is likely that the success of Exercise Four is related to students’ achievement of the target objective – describe enantiomers, demonstrated when interacting with previous Exercises One – Three (see Table 9.6.). It is likely that their prior knowledge and the images of concrete apparatus influenced the ways they responded to Exercise Four. The student’s success in this exercise might be dependent on how he/she was able to think in the microscopic world.

The results in Table 9.5. suggest that the problem solving task involving enantiomers was successfully solved by most participants in Exercise One. Furthermore, the students' discourse and the results in Table 9.5. suggest that in Exercise Two, which explored the terpene molecules, the concept of enantiomers appeared less demanding compared to the concept of structural isomers. Although factors other than the concept itself contributed to the way the students dealt with one particular task (the representations used, page overloading, student approaches to learning etc.) the results gained from this study suggest that students showed familiarity with the concepts of enantiomers. Similar findings were obtained from Study Three and Study Two and for this reason the property of enantiomers was chosen to be addressed by Exercise Four.

The interview episode given above could also be placed into the third group of responses, which involve five different participants describing how Exercise Four is a **more visual exercise** and helps to visualise what is happening with the plane of polarised light. Kate described it:

I think I liked that, I liked to be able to see the video going through the sample and going like .. No rotation or something like that, just make it simple, more realistic instead of going just .. Yes, you are right! .. um.. would be quite good to have more of these ..

As the play-back of session reached Exercise Four, Ray commented: "That was cool, that stuff with a little picture how it rotates .. the light" and appreciated the ability to see "what was happening [because she] would never have a vision like that."

Many other students also described how they "liked this exercise because you can see what is going on." May elaborated:

It's more visual, so it makes you think what it is actually doing; does this rotate the polarised light or the other one, and why? And then .. through the mixture, just to make you think oooh .., doesn't happen at all and you get the structure there, that's good..

Sue highlighted the role of animation in helping visualising quite difficult topics such as stereochemistry: "I think it's good to be able to visually see something because ... I guess, stereochemistry itself is a quite difficult, yeah.." This is similar to the description given by Rebi in which she highlighted the main reason that Exercise Four was added to tutorial:

I, sort of, .. reinforced stuff in my mind from the lectures and my previous parts .. but, I never .. I had never a visual for it, like how to relate the polarised light, we were not related that at all, like all reading all stuff, yeah ..

Finally, the last group of students' responses refers to the discussion of the structured design versus the guided discovery design that was implemented in this exercise (the way the questions were set up and the feedback was provided). This group of responses involves comparing the feedback in the form of **Confirmation - You are right!** versus the self-evaluation of whether they were right or not in their thinking that was provided by watching the animation. The responses that described Exercise Four as easier or more visual compared to the previous exercises also indicated that most of the participants were able to use the message from Exercise Four as it was designed. Observing the animation as a feedback was enough confirmation to most students and they did not need any additional confirmation for either their right or wrong predictions. Although Kate's quote was given in the group of responses **more visual exercise**, it is worth repeating it here as she clearly appreciated this kind of design when compared to the design being employed in other exercises:

I think I liked that, I liked to be able to see the video going through the sample and going like ... No rotation or something like that, just make **it simple, more realistic instead of going just Yes, you are right! ..**

During the stimulated recall interviewing most of the students (13 of 14) did not complain about the clarity of the message shown by the animation, indicating that the animation was enough and they did not need an additional confirmation. However, one participant was surprised with the changed pattern and wanted an additional confirmation:

Ooh .. that was good .. except, .., it was good as it was showing what had happened, you,.. sort of .. looked at that and you saw the little video thing and then, .. then was the end, .. and .. you know .. video, I mean if you have chosen a correct answer, you should have, **yes you are correct!** This video instead, it did replay again.. (Rebi)

When asked if she wanted an additional confirmation, she explained:

I wanted .. if they told me as well Yes that is the right answer .. I don't know, probably because if you are in the first year, probably you get things wrong and then you can work on the course, on exam. You didn't have actual confirmation, ..

yeah, it's nice to be told the, you know, you don't have to think about it .. you know, 'yes, I was' [right], I mean I want to know that I am right, you, sort of, pick it all out if you said yes, you are right.. (Rebi)

The participant mentioned above performed the tutorial in a group of three. Another group member explained:

I got it, but Rebi, the middle one, she wasn't too sure about it. They didn't say, .. like in the other questions it was actually saying, Yes you are right, this one, it just showed us, it said good, click here and it did show, you know, the rotation, but it didn't actually, .. program didn't actually say .. like .. in the other questions .. like .. you are right .. (Rose)

Although the additional help with the formal scientific explanation was available, the students did not realise it or did not want to go for help because of the pejorative nature of the word “help” (many participants explained that they did not want help, but to work out on their own).

After being shown the animation that confirmed their prediction (or decision), some students chose to go back to check the other options available. The opportunity to go back and check the other options available was another way of getting confirmation for the reasoning employed in making predictions. This option, rather than using the Help available, was preferred by many participants in the study. When asked if the students were aware of the Help available, some answered “No”, and some responded that they wanted to work it out on their own. It appeared that the use of the link Help that provided the formal scientific explanation in which students had the opportunity to check their reasoning was not readily used. (It was originally assumed that students whose prediction and observation did not agree would go for Help). Students' discourse revealed that they did not want someone's help in their decision; it was as if the word “help” removed the students' individual freedom to construct the knowledge and decide on their own.

It appeared that students did not want to be helped, but did not mind getting an additional explanation. It is very hard to explain the psychological effect caused by words “help” and “explanation” - however, when the word Help was replaced with the word Explanation, all participants who had access to the link Explanation (i.e. the last four participants) used it. The word explanation was perceived as much more friendly by the students.

(ii) Properties of Stereoisomers

Exercise Four, entitled Properties of Stereoisomers, initiated the theme of the students' awareness of the properties of stereoisomers. When the stimulated recall interview reached the point on the combined tape showing the start of Exercise Four, this seemed an appropriate moment to explore student awareness about properties of stereoisomers.

Three dimensions of this theme have been identified:

- Properties of enantiomers;
- Different stereoisomers have different properties but they were not able to identify what these properties might (could) be;
- Stereoisomers have different physical or/and chemical properties.

Within the particular dimension, the sub-dimensions were identified and discussed too. The summary of the student responses is given in Table 9. 8.

The relevance of these findings is in their broader message that exceeds the boundaries of this particular exercise (Exercise Four). They informed that an appropriate intervention might be used to initiate student conceptual development in different directions.

Table 9.8. The identified awareness of the properties of stereoisomers distributed according to different means of responding.

Participant/ Pseudonym	Enantiomers			Different isomers should have different properties – not sure what the properties might be	Different isomers have different chemical and physical properties
	Experience from Exercise Four – optical activity	Recall of a lecture demonstration	Importance in our life - Biological activity		
1. Sue			✓		✓
2. May			✓		
3. Kate			✓	✓	
4. Shy	✓		✓		✓
5. Ray	✓		✓		
6. Ruth	✓		✓		
7. Rebi					✓
8. Rose	✓		✓	✓	✓
9. Bert	✓				
10. James*					
11. Gavin	✓				
12. Josh		✓	✓	✓	✓
13. Alan	✓				
14. Jolly	✓		✓	✓	
Total	8	1	9	4	5

Pavlinic, 2000

* no data due to the technical problems that occurred in the second part of the interview

It was not surprising to find students recalling the **properties of enantiomers** because the students just finished the tutorial with Exercise Four, in which they explored the property of optical activity of enantiomers and added the knowledge gained from the exercise to their prior knowledge. Responses, such as “Like rotate the light ..” (Gavin); or “In a way they reflect the plane of polarised light “ (Rose), were collected from eight different participants.

Apart from the knowledge of optical activity, gained from the tutorial, one student also recalled a lecture demonstration that showed the polarisation of light by glucose:

I was thinking [he looks back to the tape, from computer screen to tape and back] .. yes, I didn't know what property, like, makes a difference in polarisation. .. I was thinking actually of an example done on a lecture [Glucose has been used to demonstrate the light polarisation] on optical isomers, we had glycerol, NO, we had glucose actually, what was totally different .. (Josh)

However, the most important insight was revealed in the responses which included not only the property of optical activity as experienced in the tutorial but also the recall of different biological activities of enantiomers, given to the students at the lecture. Exercise Four initiated the participants to construct knowledge by connecting different information and given by different teaching methods/strategies in the course. Nine different participants (64%) mentioned the biological activity of enantiomers, and some clearly indicated how they become aware of this property. Some students were motivated by the question “Why do chemists investigate stereoisomers?” and responded:

Is that because of the importance in our life .., because some enantimers do different things in our life and may be harmful? .. (Ruth)

Well, I think, .., the advantages of isomers, like with enantiomers which are optical isomers, are that they produce something useful, .., and yes, quite interesting because we have compounds, molecules that look similar, just mirror image but they are different compounds that have different properties and you can analyse those things,.. (Shy)

Because stereo .., enantiomers, because they've got the different biological properties and stuff, they need to know which one of them, you know, I mean which one is actually effective in a positive way. (Jolly)

Another student, stimulated by the replay of the animation for the first task of Exercise

Four, said:

It was really cool, like, related to each other because we had the whole thing on, one that was a mirror image, I couldn't actually remember what was a problem, and how the one form caused, like, in pregnant women and sometimes can get in babies, and the other form didn't, that was quite ..., and you think about it. (Ray)

It might be that students who talked about the biological activity of stereoisomers had been influenced by the story of Thalidomide they had heard at the lecture. In the quote above, Ray recalled the story, so did two other students:

Oh, yeah, that what we were discussing, because you can have some percentage of one enantiomer and compound can't be used. You can have 37 percent of one that will polarise light to the left, yeah, he [lecturer] did say that in the class .. Because they can make a drug, like that one that um, for depression, can't remember what is called, I mean, they have two on there, they have made the one which affected the babies, but they have had to isolate one, which actually costs money, to make sure they have the right enantiomer in it. I think the kids were born with, like short arms and things like that and they are still selling in some countries, ... pharmaceutical reason .. they have research with millions.. (May)

They have different physical and chemical properties. .. They have different boiling points, melting points. That's about as much as I know. I know Tony [lecturer] gave an example in a lecture, I can't remember what was it ... I think it was antidepressant, at one stage they were given and it was, they didn't realise that at the time when they produced it maybe, that they had a structural isomer and that was bad for a pregnant women, I think, yeah, so I remember that from .. [lecture], and when you are saying why it is interesting for chemists, it means very interesting because obviously if you put the wrong isomer on the market it is having bad side effects, isn't it? So, can you separate them out and I believe that it was too expensive so they are taking product off the market here although in Brazil apparently they are still have it available.. (Sue)

Although the learning from lectures was not measured in this study, these students' responses were collected as a part of exploring student use of Exercise Four. They revealed the importance of chemistry instruction on students' conceptual development. The role of telling stories in teaching and learning science is an issue advocated by Solomon (2000) for a long time, but according to the author its role has not been recognised by the wider scientific community.

The next dimension of the students' awareness of the properties of stereoisomers involved students recognising that all the **different stereoisomers have different properties** but, they were **not able to identify what these properties might be**.

Responses such as “I know that optical isomers rotate the polarised light, they show differences, um .. and the structural isomers have different properties” (Rose); or “The polarised light one, I just know that they have different properties, I don’t know what they are usually” (Josh); or “I am aware of things like rotating polarised light in different directions and stuff like that and things like, you know that there is *cis* form and a *trans* form but why? Why .. I don’t know if I can think why that is “ (Kate).

Finally, the awareness of the properties of stereoisomers in which students were more confident in describing how **different isomers have different physical or/and chemical properties**. While Rebi explained:

Um, they can have different boiling points and then they can react differently with a compound, whatever the other, you know, compound is, yeah .. melting and boiling point, something like that would be different.

Shy was even more explicit:

Um, depends on which type of stereoisomers .. some have different chemical and physical properties, some of them might be having different physical properties but not different chemical properties and things like that ..

The two participants who initially talked about not being sure of what different properties of stereoisomers might be, later mentioned that stereoisomers differ in their physical and chemical properties.

To gain additional data about student awareness of stereoisomers, students were asked about the properties of *cis-trans* isomers.

(a) *Properties of Cis-Trans Isomers*

The moment when students freely talked about the properties of stereoisomers (described above), they were additionally asked: “Do you think that *cis* and *trans* isomers have different properties?” This question was seen as a part of the previous question and aimed at revealing as much as possible of student awareness of properties of stereoisomers other than optical activity of enantiomers. Furthermore, the question was used to probe students’ thinking of addressing properties as a macroscopic dimension in teaching chemistry more than has been hitherto.

The question surprised most of the students; they didn’t expect to be asked such a question, or had never thought about it. For instance, May’s first response was “Um, ... um, it’s a good question.”

In some responses students clearly indicated they were not convinced: “I am not sure in that.” In others, although not knowing that the answer, probably due to experience with the properties of enantiomers in Exercise Four, the students were able to predict: “Yeah, they must do” or “Probably”, and some responses suggested that the students were convinced that *cis-trans* isomers have different properties; for example, short answers such as “Yes” or “Yeah.”

Most students said that they were aware of the different properties of well-known *cis* and *trans* isomers, which they used to recognise only by their different structures. When asked “What might be the properties in which they differ?” their responses were classified as shown in Table 9.9.

The findings in Table 9.9. were used to confirm the findings described and discussed earlier and given in Table 9.8.

Table 9.9. The identified awareness of the properties of *cis-trans* isomers distributed according to different means of responding.

Participant/ Pseudonym	Confusion – recall of the property of optical activity	Something must be different	Different structure	Different physical and chemical properties
1. Sue				✓
2. May	✓	✓		
3. Kate		✓		✓
4. Shy				✓
5. Ray		✓		
6. Ruth		✓		
7. Rebi				✓
8. Rose		✓		
9. Bert	✓			
10. James*				
11. Gavin			✓	
12. Josh				✓
13. Alan		✓		
14. Jolly		✓		
Total	2	7	1	5

Pavlinic, 2000

* no data due to the technical problems that occurred in the second part of the interview

A couple of the participants were confused by the question. When responding to the question about the **properties of *cis-trans* isomers** they recalled **the property of optical activity explored in tutorial**. The discourse below shows how a student clarified the ideas of stereoisomers by questioning herself:

They rotate differently, don't they? No, they can't rotate because of the double bond, I think they are different. Aren't they? They are ... I think they are different, yeah, I can't explain why they are different which is quite bad, .. I can't think of why they are different but I know they are. Um .. Oh .. yeah, but that's different to the *cis* and *trans*, that one, [points on the screen showing the task from Exercise Four] yeah I realised that they are different. (May)

Don't know what is different, but something must be different - answers such as "something must be different .. yeah .." or "I expect they have, but wouldn't know what they were", or even some of students were determined to find more about it ".. um, and I don't know pretty much of *cis-trans*, I have to find it out and, um .." were collected from seven different participants. Some students felt guilty not being able to say anything else apart from the structure (see May above), others as an apology promised ".. to find it out."

What differs is that they have different structures – Study Three, in which the conceptualisation of different isomer types was explored, suggested that students easily recognised *cis-trans* isomers from their structure and talked how the atoms/groups are arranged about a double bond. For that reason, even when asked about properties of *cis-trans* isomers, it was not so strange to get students describing the structure or the shape "would be the same structure, not really the same,..[lack of words, but used hands, fingers] different but the same" or "Well it's the shape, that way [shows by hands] and that one the other way" (Gavin). Some participants could not think of anything else but the structure.

They have different physical or/and chemical properties – The responses from five different participants involved awareness of different physical and chemical properties:

Yeah. I suppose, they have different chemical and physical properties, yeah, 'cause they are different from enantiomers .. (Josh)

Others identified what these properties might be:

Um, because they are sort of configurational isomers, so do they have different properties? They have, I know that they have usually different physical properties, like they have different melting points and boiling points and

chemical properties .. I am not sure about that ... Different chemical properties? I know they have different physical properties, but different chemical, maybe things when they do reactions, react with something or something to do with different carbons, I am not sure about that .. (Shy)

or

Um, auh .. is it something to do with the addition reactions as well, is it Markovni .. thing or something? I don't know, just guessing .. (Kate).

It was remarkable how the property has been connected with the abstract world of the mechanism in which they might react.

When the results in Table 9.9 were compared to the results obtained in Table 9.8., coherence was found for four (of five) participants who initially responded that different stereoisomers have different physical and chemical properties and described the same for *cis-trans* isomers. The participant who initially said that stereoisomers must have different properties but could not identify what the properties might be, was the one who later talked about different physical and chemical properties of *cis-trans* isomers.

Good agreement was found also for the participants who claimed that something must be different in responding to the properties of stereoisomers (three of four), describing the same for the properties of *cis-trans* isomers.

Finally, the confusion between the property of enantiomers and the properties of *cis-trans* isomers was recognised and discussed by the participants themselves.

(iii) Discussion

Students who participated in the study generally regarded the design of the added Exercise Four with enthusiasm. Most of the participants judged the design as simple and easy (cognitive), and liked the animation showing what happens (rotation/not rotation) with the plane of polarised light when a sample containing an organic compound was placed in a polarimeter tube (affective). Exercise Four enabled students to make links between the structure of organic compound (symbolic representation) and the measured property.

The task design enabled a computer to be a tool used by students for running the experiment. In this exercise, students were presented with a situation where they had to make a prediction about a property of a certain chemical compound. Then, they observed what happened in the computer animation. They evaluated their observations

and compared them with their prediction. Students were allowed different trials and were able to observe the effects of their trials. No special rewards or confirmation such as **“Great, you are right!”**, but also no punishment with **“You are wrong”** was given. In order to confirm their prediction with what was observed, the students were free to decide to go back and replay the animation (reported as useful by Kearney & Treagust, 1999, p. 10), to go for help (explanation) or to move to the next task if observation of the animation was enough.

The feedback in a form of animation and self-evaluation was well received by all but one participant. Perhaps the design employed in previous exercises (Exercise One to Exercise Three) in which the feedback contained confirmation of being right or wrong, led the student to expect the same up front reinforcement in Exercise Four. The information the student wanted was just one ‘click’ away from her, hidden in a Help link (later the name was changed into Explanation and was much more readily used than when named Help), but she did not use the Help link.

In Study Two it was observed that the participants did not understand the instruction about the availability of hints, given at the introductory page, prior to Exercise Three. When the words given in the instruction were slightly changed in this study, the participants did not show any sign of misunderstanding the on-screen instruction. The words chosen (Explanation instead of Help) and the order in which they were put together seemed to play an important role in conveying the intended information from the instructor to the student.

(a) Different Properties of Stereoisomers - Importance in Our Life

The results of Study Three were used to justify the major amendment, the added Exercise Four, which addressed the macroscopic property of enantiomers. Exercise Four promoted students to think and make links between the structure of the compound given and the property of optical activity. The students widened their awareness of stereoisomers, not only for a given type of isomerism (enantiomers), but were encouraged to think more deeply about the properties of other stereoisomers, *cis-trans* isomers for instance. Students talked about physical properties of *cis-trans* isomers such as melting or boiling points, but also about different chemical reactivity (Shy, Kate). This insight of Study Four was seen as a shift in student awareness of stereoisomers when compared with the results of Study Three, in which student conceptualisation of

isomers seldom included description of properties.

The positive student responses (both affective and cognitive) and experiences with Exercise Four confirm:

- Addressing the property of stereoisomers by the computer-based task was a good choice. Exercise Four provided the students with the opportunities to make a connection between the macroscopic nature of the substance and its symbolic-microscopic nature;
- Addressing the single aspect was well received because it did not cause conceptual overload (all participants described Exercise Four simple, easy - such cognitive responses might be due to appropriate chunking);
- The guided discovery with animation, such as employed in Exercise Four, was also well received by the participants (positive affective responses).

The results obtained for *cis-trans* isomers are slightly optimistic if compared to the results obtained in Study Three (see Chapter 8, Table 8.26.). However, the value of the results is that they indicate that the macroscopic dimension of the isomers, other than enantiomers, should be in focus when teaching about the concepts of stereoisomers.

Exercise Four was welcomed, but the need for the properties of the other stereoisomers to be addressed as well was clearly expressed:

.. I don't think I met any question to do with chemical and physical properties of, like, conformational isomers. I haven't really seen anything about physical and chemical properties there. But the optical isomers was good really .. Yeah, it goes to optical isomers really well, emphasises the point you need to know about the property of enantiomers, um, I think if we have some properties of the other types of stereoisomers, .. We need some equivalent of conformers, because sometimes I can get confused with them.. I think of structural isomers, and because I get confused .. what is actually the difference between isomers and what property do they have .. (Shy)

The completed Exercise Four encouraged the students to recall and make links to other information about stereoisomers they heard at the lecture, for example seven participants talked about biological properties of enantiomers and their "importance in our life." The significance of this insight is not only in informing about the students' awareness of enantiomers, but also in discovering that the students' awareness of phenomena in chemistry is indeed closely related to the ways the phenomena are introduced by the teacher/lecturer. In this case the story told at the lecture (lecturer's

story) had a very deep effect on students' awareness of the properties of enantiomers. This insight confirms that the story telling takes a very important role in teaching and learning science, a viewpoint long advocated by the science educator Solomon (2000).

(b) Student Reasoning/Understanding Gained in Exercise Four

The next insight that arose from the students' discourse revealed that although the students had made the correct prediction and observed the animation, their reasons and explanations sometimes showed a lack of understanding. It might be argued that this was a consequence of discovery learning. However, firstly, regardless of student knowledge prior to their use of the tutorial, before commencing Exercise Four the participants went through Exercise One – Exercise Three, in which they had an opportunity to solve problems and/or revise concepts that underpin Exercise Four (e.g. enantiomers, stereocentre). Secondly, in Exercise Four the students were able to reach the formal, scientific explanation (Explanation link). Therefore, in guided discovery based on the design of POE tasks the students are encouraged to construct their knowledge with an opportunity to check (negotiate) their constructs with the formal, scientific explanation, which is in line with Vygotsky's sociocultural constructivism.

As shown by Table 9.10., four different groups of the reasoning employed by the participants in dealing with the tasks of Exercise Four were identified during the evaluation of whether or not the intended learning objective of Exercise Four was achieved (connection of the property of enantiomers with the chemical structure).

Eleven different participants described how they knew that they should look for a stereocentre and four different groups around it and went on to confirm their reasoning. They described that they had learnt what a racemic mixture is (Sue and May).

In explaining the way she approached the tasks, Jolly described how initially she was not sure what she should look for when assigning (predicting) the property of optical activity. In doing Exercise Four she shifted her reasoning to a more clear, simple and efficient way:

I learnt that when I am looking for enantiomers I look for a stereocentre straightaway, while before I would look for enantiomers as mirror images, but, if I looked at the one I worked on I wouldn't know what I was looking for, while now I look straight forward at that, um, and that rotates polarised light.. um, .. [pointed at the on-screen structure having stereocentre].

Table 9.10. The reasoning employed in dealing with the tasks in Exercise Four and the evaluation of achievement of intended learning outcome of this exercise.

Participant/ Pseudonym	Reasoning				Learning objective	
	Looking for stereocentre/fou r diff. groups	Shift from not sure - stereocentre	Own reasoning /nonsuperimposab le mirror images	Guessing	Achieved	Not- achieved
1. Sue	✓				✓	
2. May	✓				✓	
3. Kate	✓				✓	
4. Shy			✓		✓	✓
5. Ray	✓				✓	
6. Ruth	✓		✓		✓	
7. Rebi	✓				✓	
8. Rose	✓				✓	
9. Bert	✓				✓	
10. James				✓		✓
11. Gavin				✓		✓
12. Josh	✓				✓	
13. Alan	✓				✓	
14. Jolly	✓	✓			✓	
Total	11	1	2	2	12	3

Pavlinic, 2000

Two participants worked through the tasks using their own reasoning. Being surprised with an unexpected response, Shy looked for additional information in Help, but rejected a given explanation that did not fit her own reasoning. The interview episode with Shy below confirms that:

R: Why did you choose this one?

Shy: Ooooh, um, I think it was, .. um, .. I did that molecule there as before, seems OH going to the right, I was thinking if you do a mirror image of that, then it's the OH is on the left hand side where it is opposed on the right hand side, so I was thinking that was nonsuperimposable, so I said it would polarise light. Then I clicked on Help, why I was wrong and it said it doesn't polarise light because it doesn't have a stereocentre, but I am not sure whether that was used in the lecture. I can't remember definitively, but, I always thought in my mind that if it's not a nonsuperimposable mirror image, then it cannot, but then it can polarise light, so that's why I clicked that, obviously that was wrong ... I was actually thinking about nonsuperimposable and superimposable mirror images, I didn't think about a stereocentre, I always thought of that first when I was thinking about polarised light, so I think that was why I was wrong, yeah, yeah .. I have to ask Dr Wright about that.

Later on, and facing the same problem she was asked:

R: Right, why didn't you go for help here? [Help link appears on the screen]
Shy: Oh, because I knew it would give me the same hint, it will probably give me the same hint, just say it doesn't have a stereocentre, because I knew that my answer was wrong and I didn't go for a help..

The reasoning described and employed by Shy (and also identified by another student Ruth) is a strategy that could lead to either the right or the wrong solution. Imagining a mirror image of a compound given, and testing to discover if the two are superimposable or not is a very complex task. When the strategy was connected with the other components used for assigning the property, such as used by Ruth "looking for a chiral centre", it ended with a correct solution. However, sometimes as in the case described above by Shy, the prediction failed. Stereochemistry concepts are indeed difficult and the terms describing them are strange. It takes time before a student memorises terms and the associated meanings for them. It may be that some students, such as Shy, hardly accept that a simple explanation or solution (such as looking for four different groups around stereocentre only) could work for a complex problem or concept.

Finally, one participant admitted that he used guessing in Exercise Four and did not go for the help provided:

To be honest, most of them was just guessing, I'm still a bit .. [shaking his hands] if I really understand that (Gavin)

while the guessing was a strategy employed by another participant not only in Exercise Four but in dealing with all tasks in the tutorial.

In conclusion, the strategy employed by the students was used in evaluation of whether the intended learning objective of this exercise was achieved or not. The learning outcome achieved assumed that the relationship between the structure and the property of optical activity was explained in agreement with the formal, scientific explanation during the interviewing process and applied in solving problems. The evaluation involved the analysis of an individual student's reasoning applied in solving problems and whether or not the explanation for the relationship between macroscopic property of the optical activity and the structure, given during the interviewing process, agreed with the formal, scientific explanation.

The numbers in Table 9.10. indicate that most participants achieved the intended learning objective (twelve out of fourteen; with a strategy of one participant evaluated as both achieved and not achieved). The design of Exercise Four provided a clear message to most participants. The student who used guessing (Gavin) was amazed at the simplicity of the task once he reached for Help, but that was at the very end of the exercise (and the tutorial).

The high number of students who achieved the intended learning objective in Exercise Four is optimistic. However, it is hard to compare the student achievement in Exercise Four with the achievements of selected task objectives in Exercises One – Three because of the very different objectives and different exercises. In addition, the analysis procedure for Exercise Four differed from the one used in the first three exercises.

The ability to analyse student reasoning was one of the great strengths of the stimulated recall interviewing combined with the design employed in this exercise (prediction-observation-self evaluation). Kearney and Treagust (1999) concluded the same for their POE procedure.

9.5. CONCLUSIONS

9.5.1. Study Four – Outcome of the Research in Previous Studies of the Thesis

The first insight of this study emphasises the importance and usefulness of applying educational theory constructivism and particularly exploring student ideas in developing learning tasks, such as a computer-based tutorial.

In order to answer the Research Question for this study:

How do students interact with an in-house authored, chemical concept - centred computer-based tutorial, amended to take account of student prior knowledge and approach to learning?

the analysis of how students found the amended tutorial took place. Two kinds of amendments that had been made narrowed the focus of the study. The amendments that followed the original design of the tutorial (e.g. feedback in Exercise One – Exercise Three, improved instruction and navigational links) are called the minor amendments,

while the added Exercise Four, which differed in focus and design when compared with the rest of the tutorial, represented the major amendment of the tutorial.

The minor amendments, made after the results of both Study Two and Study Three, provided better instruction delivery (introductory page to Exercise Three), better feedback (more representations were added and the hints were used), and better navigation to the glossary (the glossary was used by most participants). However, the use of complex molecules in the tasks addressing stereochemistry concepts appeared to be the one of the major barriers in achieving the intended concept-related objectives. This was the insight that emerged in Study Two and was confirmed in this study, indicating that more educational research is needed in exploring this phenomenon.

Exercise Four, based upon the results of Study Three, was a major amendment to the tutorial and explored the optical activity of enantiomers, the only property of stereoisomers the students mentioned when describing the ways they conceptualise each isomer type.

The ways in which students talked about Exercise Four showed how this added exercise widened their awareness of stereochemical phenomena, added a new dimension to the knowledge they already had from school and lectures. Exercise Four provided the students with a new experience, a new way of thinking about or describing phenomena, a way they had never experienced before. This new breadth in the students' experience opened up the possibility of enhancing and deepening their understanding of stereoisomers. Positive students' responses to the concept (investigating the properties of enantiomers), as well as to the design of Exercise Four (guided discovery, animation) confirmed that the exercise was a useful amendment.

9.5.2. Guided Discovery with Computer Animation

The second insight from this study refers to the use of the knowledge in computer development in conjunction with the educational theories in designing educational software such as employed in Exercise Four.

The positive student responses to Exercise Four, in the sense of student satisfaction, were identified for both the aspect - exploring of the property, and for the way the concept was addressed (guided discovery with animation). The use of animation in addressing the optical activity of enantiomers proved to be successful in providing the

macro-symbolic-micro link. This suggests that this type of application of CAI, if combined with a carefully chosen concept, could be an appropriate way to successfully address other chemistry phenomena, which are similar in nature to this one. The computer animation showed the advantage over the traditional educational tools because it enabled the students to see a visualisation of the process of the rotation of the plane of polarised light, not observable while performing the real experiment.

The experiment of Exercise Four is an indicative experiment of where tutorial design should go. The positive results suggest that this type of educational software could be much more widely used to guide the students' attention to the particular dimension of the concept and to provide the students with the opportunities to make links between different dimensions of the concept (macro-symbolic link or their dream world - real world of chemistry phenomena).

In addition, in order to bring about better learning and therefore understanding of chemistry, similar kinds of intervention could be applied in other forms of chemistry instruction, and for other concepts chosen.

10. FINAL DISCUSSION

This chapter will discuss the main insights from the four studies described in the thesis, concentrating on their relationship and their general educational implications.

10.1. FOUR STUDIES –THE COMPLETE PROJECT

The project that included four studies demonstrates the effective use of educational research in developing chemistry-learning tasks, in particular the development of a computer-based stereochemistry tutorial.

10.1.1. Contributions from Study One

Study One investigated the present position at the time, i.e. the effectiveness of the commercial software used in the chemistry course at Massey University in 1997. The results obtained showed the essential features of the software design necessary to meet the needs of the wider group of students. Apart from the importance of the selection of the chemistry concept to be addressed by the software, the results also indicated that the software applications, when employed in laboratory classes, were welcomed as an addition to, and not as a replacement for, hands-on experiments.

There were three important outcomes from Study One. The first was that student achievement of intended learning outcomes when interacting with commercial software was moderate and similar to that reported by Wainwright (1989) or Williamson and Abraham (1995), and was in agreement with the general trend of the effectiveness of computer-based instructions reported by Fletcher-Flinn and Gravatt (1995). The study also revealed possible reasons for the mismatch between the promises of CAI and the learning outcomes. These reasons were attributed to the selection of the chemistry topic and type of software design and its application. The multi-faceted method developed for examining student-software interaction and evaluating student learning (involving videotaping and stimulated recall interviewing) revealed insights that would never have been revealed using the one technique only (e.g. audio taped interviews).

10.1.2. Contributions from Study Two

The insights given in Study One, together with the knowledge of the theory of constructivism were used in 1998, when the development of chemistry software took place in Study Two. The computer has advantages not possessed by other educational tools, and these were considered in the software design of the carefully chosen topic of stereochemistry. The design involved the use of multiple representations for stereochemical concepts (2D - symbolic and 3D - on screen interactive micro models), branched design that enables free navigation through tutorial, adaptive feedback, glossary of the main concepts and solving problems that increased in complexity as the students progressed through the tutorial. The students were able to move through the tutorial at their own pace, to interact on-screen with the 3D ball and stick models, to select the representation that best suited them or the problem, and to repeat the task as many times as necessary until the achievement of intended learning outcomes or student satisfaction was achieved. All those software features were well received by the participants.

The results obtained proved that the software, integrating learning theory, constructivism and the features specific to the particular chemistry concept, provided better student-software interaction than Study One. These results were obtained by the application of PCK of those involved in the development of the tutorial, in recognising the critical aspects in student learning of a particular concept and the advantages of computer use to address those aspects.

The results of the use of multiple representations generally agree with the reports by Gabel (1999). However, the results of this study identified what the advantages and difficulties were for both 3D interactive ball and stick models and 2D skeletal structures that were employed in the tutorial. On-screen 3D interactive ball and stick models were new experiences for all participants. The positive student responses to this way of representing molecules suggest that the computer should be used in addressing the concepts that require 3D visualisation. Despite the familiarity with the skeletal structures, some participants described the problems in understanding this type of representation. The students appreciated the possibility of having the different representations so they could choose the one that better suited them or the problem being investigated. When faced with the tasks that required transition from one

representation to another some of the participants reported problems. Student understanding of the concepts of stereochemistry was re-challenged when the tasks moved from those involving simple to those involving more complex molecules. This was an area identified as important to be investigated in the future.

The study also proved that the usefulness of any on-screen instruction could be judged only by the students who use it, and who either found it useful (e.g. multiple representations, feedback in the tutorial) or not (availability of glossary or hints).

10.1.3. Contributions from Study Three

The insights of the student use of the tutorial from Study Two were useful, showing how the students experienced the features of the design, but also indicating minor omissions in the tutorial.

However, the tutorial in Study Two was designed from the instructors' viewpoint (the views of the members of the group involved in the tutorial development) and at that stage no students' ideas were considered and integrated into the tutorial design. For that reason Study Three, which explored students' ideas that underpin their understanding of stereochemistry, took place in 1999. The phenomenographic approach that was employed resulted in different hierarchically ordered categories of the ways in which students visualise molecules, relate the macroscopic sample of the substance to their visualisation and conceptualise each isomer type.

The power of the carefully planned methodology (in depth interviews) provided the conditions in which an additional insight into the way students experience chemistry phenomena was gained (students' responses to the sight of 'real' colourless liquid). This new insight in the study indicated the separation of the real and the abstract worlds of chemistry and was named the dream world–real world phenomenon.

Students' discourse in Study Three suggested that the students' knowledge of chemistry is likely to mirror the ways chemistry has been taught to them. Students today, for example, make use of more micro models in their 'dream world' as these have been more emphasised in the teaching of chemistry. The participants explained that they visualise molecules in one way or another because "I have been taught so". The students mostly recalled what they had been taught at high school, apologising for still not being able to visualise what they are taught at university ("I know that I am

supposed to think of molecules like space filling ones, but I still tend to visualise them like this [pointed by finger on linear structure]"). This is in agreement with what was discussed earlier by Laws (1996), Ramsden (1993) and Shepard and Gilbert (1991).

One of the subcategories of the ways the students related the 'real' liquid of 2-butanol to the previously described visualisation of 2-butanol (mostly symbolic and/or micro) was the association to laboratory classes. The role of laboratory classes in understanding chemistry and in bridging the gap between the macroscopic and the other two abstract dimensions of chemistry is recognised by teachers, although, according to Hodson (1993), its role is debatable. The results of this study suggest that more efforts at all levels of instruction should be taken in order to help students to overcome the gap between the two separated worlds of chemistry.

The results obtained suggest that student visualisation reflected (a) the ways chemistry was mainly taught and (b) the time spent in dealing with chemistry. This highlights the crucial role of the teachers (experts) and the instruction in the process of students' enculturation into chemistry, and the role of the experience or practice in chemistry gained over a period of time.

The results showed that 2-D structural representation on the page still seemed to have power and usefulness (representing a greater truth about chemistry) for most students, despite the more sophisticated representations of electron maps ('fuzzy balls' as called by the participants) taught to approximate reality at university. Students' descriptions indicated their very strong intention of measuring up to what they thought the teacher expected they should think or be able to predict. When some mentioned that they preferred earlier representations, they sometimes could not resist apologising, believing that they ought to wholeheartedly embrace the new paradigm, but nevertheless (by implication) finding nothing in it to cause them to make a change.

The insight of two worlds of chemistry separated from one another, a phenomenon, called in this study 'dream world - real world' concept, is a contribution to our general understanding of the way learning chemistry takes place. The 'dream world - real world' concept is a contribution to the discussion on learning in chemistry laboratories, and might be used as a possible explanation related to the wonders of learning and nonlearning in chemistry laboratories (Draper, 1998; Hodson, 1993; Johnstone 1997; Lagowski, 1989; Solomon, 1988). If the dream world-real world concept is recognised, then the finding that many students were not aware that stereoisomers differ in their

properties becomes understandable. Properties of stereoisomers are part of the real world of stereochemistry and do not easily enter the other, different world of stereochemistry of which the students were mostly taught.

10.1.4. Contributions from Study Four

The results of Study Three influenced the major amendment in the tutorial that took place in Study Four, in 2000. The additional effort to address the complex stereochemistry concepts from the macroscopic aspect was made in the added Exercise Four. Most computer programs are aimed at giving the students the ability to negotiate their dream worlds of chemistry with the abstract nature of different conceptual representations/models in chemistry. This was the aim of the initial design of the computer-based stereochemistry tutorial. With Exercise Four, students are given the opportunity to integrate their dream world of stereochemistry with the real world of stereochemistry. The results obtained from Study Four indicated that talking about properties of isomers (and not only about optical activity of enantiomers that was experienced in the amended tutorial) became an integral part of the participants' discussion during the interviews. This was a shift from results in Study Three, in which the students' descriptions of different isomers were generally based on discussing structures with few showing awareness that different isomers have different properties.

The results obtained from Exercise Four also showed how the appropriate design employed in chemistry teaching software, which involved an animation and guided discovery, promised to offer an innovative instruction and a more effective learning of chemistry and in a way that was described by the participants as "easy", "simple" or "more visual".

Again, exploration and evaluation of the student-software interaction and all these results would not be obtained without the multi-faceted method, developed for this project.

The study showed how educational research could be used in designing chemistry learning tasks. Goforth (1994), Lower (2000) and Schaefermeyer (1990) suggested that, if well designed, CAI is a type of instruction that matches many of the assumptions of constructivism. However, not many studies indicated that the design of software tasks was based on the research into student ideas. Therefore, the research in this project is a

contribution to constructivist-based research in general, and in particular to that related to educational software.

Most of the findings from Study Two were confirmed in this study, which increased the validity of both Study Two and this Study Four. The minor amendments in the tutorial made the on-screen instructions easy for the participants to understand, and therefore provided the better student-software interaction.

The multiple aspects collected in Study Three resulted in Exercise Four which addressed the property of enantiomers (macroscopic dimension). This was an attempt to bring together the real world of stereochemistry with the abstract dream world of stereochemistry. It also employed guided discovery with animation as a feedback, which enabled self-confirmation. This proved to be an efficient way in providing the instruction. Most students were able to develop their understanding by observing the animation and made the connection between the properties of enantiomers and their structure.

The positive student responses to Exercise Four and the results of student understanding (Table 9.10.) suggest that the design of chemistry software, such as that employed in Exercise Four, is a way in which the computer can perform a unique and invaluable function in the process involved in learning chemistry (or other scientific subjects), a category of instruction different from laboratory measurement or theoretical discourse, but enhancing both.

10.2. IMPLICATIONS OF THE RESULTS IN TEACHING CHEMISTRY AND CHEMISTRY SOFTWARE DEVELOPMENT

The results obtained have their implications for teaching chemistry in general, and stereochemistry in particular. They are also important to all who use chemistry software or make an attempt to develop their own.

10.2.1. Teaching Chemistry and Stereochemistry

Chemistry teachers should be aware of the advantages of using multiple representations in instruction, but also of the difficulties the students, who are to learn from the

instruction given, might face. In a classroom with a range of chemistry backgrounds, when a teacher switches from one representation to another during instruction, it is always possible for some students to get confused. For that reason, teachers should consider firstly, that they make clear to the students the purpose of the shift taken from one representation to another and secondly, that they make sure that the students understand the multiple representations used.

The results of the studies described in the thesis (Study Two and Study Four respectively), suggest that chemistry teachers should use simple problems in their instruction but expand their application and use the more complex problems, so the students will practise them and learn about the applications of the concepts in more real situations.

The part of Study Three, which investigated student conceptions of different isomer types, resulted with the recommendations to teachers specifically for each isomer type. From the phenomenographical point of view, one of the recommendations common to teaching all isomer types would be - in order to increase the students' understanding, the teachers should provide the students with more variations in instruction.

The insights from Study Three (dream world – real world concept) showed that aspects important in student learning could be discovered from examining student conceptions only.

Although teaching was not analysed in this study, the results suggest that student learning of chemistry is closely related to the ways chemistry is taught to them. This emphasises the role of teachers and the instruction given to the students. It was discussed in Chapter 8 that the participants' visualisation reflected the students' attempts to describe molecules on the basis of what they were taught at high school or at university. An awareness of what would be an appropriate visualisation for 'university standards' was shown by many participants. The participants who still preferred to visualise molecules in a way they were taught at high school could not resist apologising because of not being able to visualise in 3D representations (space filling models) that were used in lectures at university. This led to the conclusion that students' visualisation mostly mirrored the ways chemistry was taught to them. Laws (1996), Ramsden (1993) and Shepard and Gilbert (1991) discussed the view that students' science conceptions and their learning approaches are influenced by the ways in which knowledge is structured and presented to them. Ramsden (1993) argued that different

teachers frame different curricula for students and in a real sense, they teach different things and students learn different things from them. Students' visualisation was based upon teaching strategies and the knowledge structured and presented to them at high school, with some attempting to include as much as possible from the knowledge structured and presented to them at university. The time spent with the knowledge structured and presented to them in one or another way is one of the most likely factors that influenced students' visualisation. This discussion is even more relevant to student learning of stereochemistry.

Many students' quotes can be found in four studies described in the thesis to support this.

Caly said:

.. the thing with chemistry means you get taught something and you go along with that, that's fine .. (Caly, Study Three)

The discussion above is supported by sociocultural constructivism in which a teacher helps learners to construct knowledge. Cara described:

I think, I really appreciate my chemistry teacher so he used, he spent ages telling us about the shapes and stereoisomers, .. I think a lot depends on the teacher explaining it, so you know, it helps if somebody else has done it and talks about it rather than just you try to read it through on your own, 'cause I found really true helps backup what you've been taught, but is important that somebody else there helped you go through that you understand it. (Cara, Study Three)

Paul, a participant in Study Three described how his learning is based on listening to the lecturer and that "someone else's ideas" help him to develop his own understanding. It was also discussed that teaching and learning chemistry has elements of enculturation as assumed by Vygotsky's sociocultural philosophy.

The next message to the teachers follows from the concept discovered in Study Three that showed that students perceive chemistry in two worlds, the body of chemistry knowledge separated from the real world of chemistry, the 'dream world – real world' concept. This is not a phenomenon specific to the participants in this study, but is equally valid to all who deal with chemistry. However, with students-learners who have not developed enough knowledge and experience in chemistry and in all its forms over a period of time, the separation is very wide when compared to those of the chemists or teachers. The failure to recognise this divide might be one of the problems at the heart

of teaching modern chemistry in the schools and universities. Teachers should take every opportunity in attempting to bridge the gap between the two worlds of chemistry either during the instruction of new concepts or after the concepts have been mastered.

10.2.2. Teachers Choosing or Developing Chemistry Software

The insights obtained in Study One are important to the teachers choosing and implementing commercial software or developing their own software. They showed that preliminary investigation and literature review are prerequisites for chemistry software development. Even so, educational research is needed to measure the effectiveness of any on-screen instruction. Teachers should be aware of the extent of enculturation that any instruction promotes. From the learner's aspect, the instruction could be judged as good or not, only as understood by its users (learners).

A close fit between a piece of courseware and its situation of use that is specific (Draper, 1998) seems to describe successful chemistry software, with advantages of own-developed over the commercially available because of the possibilities for amendments.

For the successful use of educational software in chemistry, the developers should follow a design similar to the one employed in Exercise Four; that is a carefully chosen topic and the aspect of the topic to be addressed, one aspect at a time, no page overloading, short task duration and employing a design such as guided discovery with animation. In addition, the software should target the concepts in which the use of 3D representations have an advantage over the 2D representations.

10.3. SUGGESTIONS FOR FUTURE RESEARCH

The research described in the thesis suggests that computer supported learning with the on-going development with respect to both technological and educational aspects should be constantly evaluated. In addition, the evaluation of the effectiveness of educational software should be based on how the particular piece of software is received by its user – student.

Because computer supported learning provides opportunities for new kinds of learning, not achievable by using traditional educational tools (e.g. lectures), more research is needed to reveal as much as possible about these new kinds of learning. In addition, the

evaluation of these new kinds of learning needs new criteria as different kinds of learning are hardly to be compared to one another.

This project was done to gain more general insights about the effectiveness of computer supported learning of chemistry. There is a need to acknowledge that the notion of enculturation could provide a good theoretical basis for a future analysis of the data collected in this research.

Out of many insights gained some of them were selected as those just diagnosed/identified as important, but due to a lack of time not analysed in detail.

The first such insight refers to peer tutoring in a computer-based environment, which was not analysed and discussed enough in the studies described in the thesis. There were indications of the benefits but also constraints of student-student cooperation in front of the computer screen. The computer-based tasks can be designed to promote such learning. The stereochemistry tutorial was not specifically designed for peer tutoring; it was left to the students to decide whether or not they prefer working individually or in groups. From the point of view of data collected for the research purpose, the amount and quality of data gained from student-student conversation when working in groups was enormous compared to those gained from individual interviews.

The second insight that needs additional research informed about the learning difficulties students face when learning chemistry in general; a transition from the understanding of a concept gained using simple molecules to confusion caused when the complex molecules were used. This insight is particularly important in learning chemistry at university level because students, soon after completing the first year chemistry course, need to deal with complex molecules in their other courses based on chemistry (e.g. biochemistry).

The third insight refers to difficulties students faced when dealing with a particular chemistry concept, i.e. three-dimensional crystal structures in Task 3, Study One (unit cells, cavities etc.) and the effectiveness of computer-based animations in helping students to understand this topic. This piece of software application was part of Study One but was not explored enough due to lack of time and the overall aim of Study One. Whether for the reason of the concept itself or the type of computer supported application, the poor students' discourse indicated that more research is needed with more narrow focus to address this topic.

Finally, the participants themselves responded positively to Exercise Four (Study Four) that addressed the properties of enantiomers, but clearly expressed the need that the properties of other stereoisomers should be addressed in a similar way. This is an area to be targeted by research in the future with or without development of educational software.

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