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Applying Bifocal Displays to Data Visualisation

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Abstract

Rapid advances in communications and computer technologies in recent years have provided users with greater access to large volumes of data from computer-based information systems. The issue of the relatively small window through which an information space can be viewed brings with it two associated problems: presentation and navigation. This research is based on an approach called the Bifocal Display proposed by Spence and Apperley to address these inherent difficulties common in large information spaces in modern computing environments. The essence of this presentation technique is to provide the user with detailed local content as well as a global context to facilitate navigation.

In this research, the original one-dimensional Bifocal Display concept has been extended in two-dimensional form to deal with two fundamental types of large information spaces: those with a high information density, for example, large databases and spreadsheets, and those with inherent spatial relationships, such as topographic maps and networks. An experimental study has been carried out to study the usability of the Bifocal Display and other presentation techniques based on various implementations of the London Underground map. Results have shown that the Bifocal Display is a usable and effective approach for the presentation of large information spaces.

Presentation techniques can be broadly classified into distortion-oriented and non-distortion-oriented; the former generally requires more computational resources than the latter. With the increasing processing power of personal computers, researchers have developed a variety of novel distortion-oriented presentation techniques. Unfortunately, the distorting appearance resulting from the application of these techniques, coupled with the growing number of new terminologies used by researchers, has caused some confusion to the graphical user interface designer. A taxonomy of

distortion-oriented techniques based on their magnification functions has been proposed to facilitate the identification of the similarities and differences of these techniques. A conceptual model has also been put forward to unveil the underlying principles which govern their operations.

Despite the variety of novel presentation techniques currently available, the choice of a technique in a particular application remains very subjective; there is a general lack of selection guidelines or methodologies. An evaluation framework E^3 has been developed to provide a basis for the comparison of different presentation techniques, given the nature and characteristics of the data to be presented, and the interpretation required. E^3 focuses on three aspects of graphical data presentation: expressiveness, efficiency and effectiveness. This framework lays the foundation for the development of a set of metrics to facilitate an objective assessment of presentation techniques.

A general visualisation tool, the InfoLens, has been designed based on the theoretical framework of this research. The design of the InfoLens has further demonstrated that the Bifocal Display is an effective approach to visualising large information spaces.

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Publications

The following publications have been prepared in the course of this research:

1. Leung, Y.K. (1989): Human-computer interface techniques for map-based diagrams. In *Advances in Human Factors/Ergonomics* , Vol 12B: Designing and using Human-Computer Interfaces and Knowledge Based Systems, (Eds. Salvendy, G. and Smith, M.) Amsterdam, Elsevier, 361-368.
2. Howard, S. and Leung, Y.K. (1991): Interacting with graphical user interfaces. *Proceedings of OZCHI '91*, Sydney, November 1991, 47-52.
3. Leung, Y.K. (1992): A comparative study of graphical user interfaces for topological maps. *Massey University School of Mathematical & Information Sciences*, Report Series A No. 92/1.
4. Leung, Y.K. and Apperley, M.D. (1993): A taxonomy of distortion-oriented techniques for graphical data presentation. In *Advances in Human Factors/Ergonomics* , Vol 19B: Human-Computer Interaction - Software and Hardware Interfaces, (Eds. Salvendy, G. and Smith, M.), Amsterdam, Elsevier, 104-109.
5. Leung, Y.K. and Apperley, M.D. (1993): E³: Towards the metrication of graphical presentation techniques for large data sets. In *Lecture Notes in Computer Science Vol 753: Human-Computer Interaction*, (Eds. L.J. Bass, J.G. Gornostaev and C. Unger) Berlin: Springer-Verlag, 125-140.
6. Leung, Y. K. and Apperley, M.D. (1993): A unified theory of distortion-oriented presentation techniques. *Massey University School of Mathematical & Information Sciences Report* , Series A No. 93/1.
7. Leung, Y.K. and Apperley, M.D. (1993): Extending the Perspective Wall. *Proceedings of OZCHI '93*, Canberra, November 1993, 110-120.

8. Leung, Y.K. and Apperley, M.D. (1994): A review and taxonomy of distortion-oriented presentation techniques. *ACM Transactions on Computer-Human Interaction*, 1, 2, 126-160.
9. Leung, Y.K., Spence R. and Apperley M.D. (1995): Applying Bifocal Displays to topological maps. *International Journal of Human-Computer Interaction*, 7, 1, 79-98.

Chapter 1

Introduction

"We are entirely convinced the future is 'visual'. We believe that in the next few years many more of our daily technical and scientific chores will be carried out visually, and graphical facilities will be far better and cheaper than today's. ... They (languages and approaches) will be designed to encourage visual modes of thinking when tackling systems of ever-increasing complexity, and will exploit and extend the use of our own wonderful visual system in many of our intellectual activities."

Harel, 1988

1.1 Accessing Large Information Spaces

The computerisation of information systems, coupled with better communication facilities and ease of connection to remote sites in recent years, has resulted in the exponential growth of information confronting the computer user. In performing a typical task on the computer, the user is often required to spend a large proportion of his or her time at the workstation locating various pieces of information stored in the system. Tools which would assist the user to locate specific information in these information bases could therefore significantly improve productivity and efficiency.

In the context of human-computer interaction, information retrieval goes beyond just the location of a piece of data; it also encompasses comprehension and understanding of the data presented by the system. There are two levels of difficulty

associated with information retrieval over a small display screen on which large information spaces can be presented. At the upper level, the problem relates to the management of various information sources. Window-oriented systems allow the user to see information from several tasks, but severe conflicts among tasks contending for the limited screen space available may lead to high overheads engaged in task switching activities. At the lower level, the problem is one of locating items within a large information space over a small display screen, once the desired window is selected. Often, the user encounters difficulty in navigating within this information space, and in extreme cases, can get completely disoriented in it.

Visualisation is emerging as a key concern for a wide variety of applications. It brings the human visual system with its pattern recognition capabilities to bear in either exploration or portrayal of information (McCormick, DeFranti & Brown, 1987). Large complex data sets are displayed in ways to allow the viewer to investigate the global nature of numerical solutions and to explore analyses visually. Visual programming systems represent algorithms in ways that may improve clarity and simplicity of expression, as well as manage complexity in large systems (Shu, 1988). In knowledge engineering environments, systems often supply graphical representations of rules and facts, and effective knowledge visualisation systems have been developed (Patel & Sutcliffe, 1993). Even hypertext systems, which are predominantly textual in content, typically rely on visual representations for navigation and orientation (Conklin, 1987).

Interacting with a small display surface

Whilst the visual channel is the key means of computer-to-human communication in the computing system, the limited screen space available on the display monitor places a serious constraint on its effectiveness. Many knowledge intensive computer applications require that the user interacts with a considerable number of objects, often residing in different parts of the system. In order that the user can examine, manipulate and track these objects, they should be readily visible.

When humans perform tasks with paper, current information is usually managed using a horizontal two-dimensional space in the form of a desk. The person organises his or her sources and reference (books and papers) on the table in such a way that visual arrangement provides memory cues that organise and ease the performance of the tasks. Henderson and Card (1987) compare the sizes of desks and tables with various display screens and suggest that the size of a typical dining table is equivalent to 119 Macintosh 9" screens; if the effects of resolution, grey scale and colour were considered, the comparison would be more extreme. The desktop metaphor has been designed around these ideas; the work environment on the computer is presented to the user as if he or she

is working with paper documents. Whilst computer displays are much smaller than desks or tables, files and folders are hierarchically organised and represented using space-efficient icons on the computer screen to facilitate easy access and interaction.

It is well recognised that screen real estate is a scarce commodity and interface designers strive to use this valuable resource efficiently and effectively. Indeed, there are systems available on the market now which support multiple display screens to extend the immediate workspace accessible to the user. In the Macintosh system, for example, two monitors may be configured to form a continuum of work area. However, these systems are costly and moreover, even with these extensions, the display areas are generally not large enough to support the number of non-overlapping windows typically used in a multi-tasking environment.

Despite the multitude of techniques available to address the small-screen problem, the fundamental difficulty that not all the information may be viewed by the user brings with it two issues: navigating around the information space and the simultaneous viewing of information situated in different parts of the workspace. The issue of navigation relates to the problem of finding the way to locate the desired information without getting lost in the workspace. There is a need to provide the user with a global as well as a local view of the information space. The issue of simultaneous access to separated information can often be overcome with multiple focus presentations using a distortion technique or a multiple linking mechanism such as those in hypertext systems.

Switching Tasks

In a typical work environment, the user writes a paper, reads and responds to electronic mail messages and news items, looks up databases and performs housekeeping on the computer files. The variety of these tasks to be carried out by the user often demands constant switching of attention from one task to another; especially in situations where mail messages are transmitted and received asynchronously. In the course of these task switching activities, users have to move, reshape and scroll windows, make selections on menus, shrink and expand icons using a pointing device or even type in commands through the keyboard. Bannon, Cypher, Greenspan & Monty (1983, cited in Card & Henderson, 1987) identify a number of situations in which users switch from one task to another:

- (1) user digresses to perform tasks that users remember while carrying out another task;
- (2) user time-shares among concurrent demands;

- (3) user is working on a task with long waiting periods;
- (4) user performs subtasks which relate to the main task;
- (5) user runs into a snag and perform error recovery tasks;
- (6) user may be interrupted by external sources; and
- (7) user shifts to a specialised environment.

Some of these task switching operations, are required as a result of the limited screen space available to support multiple non-overlapping views to be displayed simultaneously. Bannon *et al* also suggest six areas to consider in interface design, to support task-switching:

- (1) reducing the user's mental load when switching tasks;
- (2) facilitating speedy suspension and resumption of activities;
- (3) maintaining records of previous activities;
- (4) defining functional grouping of previous activities;
- (5) supporting multiple perspectives on the tasks at hand; and
- (6) providing interdependencies among items in different workspaces.

In designing their Rooms system to facilitate task switching in a window-based graphical user interface, Henderson & Card (1987) take the view that there are specific issues which relate to task switching. One example is the amount of time it takes to perform the switching and the mental complexity of remembering how to invoke the other task and of trying to get into the mental context. They propose a refinement of Bannon *et al*'s list with four specific areas of consideration:

- (1) The interface should support fast task switching, fast task resumption and enable the user to re-acquire the mental task context easily.
- (2) The interface should provide access to a large amount of information relevant to the task at hand, quickly and with minimal overhead activities.
- (3) The interface should support clustering of phases and transitions of user activities to minimise 'window faults'.
- (4) The interface should provide the user with engaged tools, or a collection of tools, sharable among several tasks and they should be presented to the user in a task-specific manner.

The Rooms system has been designed around these concepts and a variety of facilities have been implemented to support task switching activities.

Information access and retrieval

One of the primary goals of visualisation is to help manage and understand large amounts of information. From this perspective, information retrieval systems for large databases are natural application domains of visualisation techniques. The time it takes for the user to gain access to a document, a screen or a piece of information is a quantitative measure of the efficiency of this information retrieval process. This information retrieval time can be broken down into two components: the time it takes for the user to provide the relevant keys to enable the system to begin the searching process and the processing time involved in locating the desired information. Research efforts in data structure, compression techniques and information retrieval theory, coupled with the increasing computational power of computing machines, have all contributed to significant reduction of the processing time involved in searching. The time it takes for the user to input the search keys into the system is often much longer than it takes the computer to perform the search. The bottleneck of information flow lies clearly with the human-computer interface, and the design of an effective interface to present information still remains a major challenge to be tackled in an information retrieval system.

The standard formulation of the information retrieval problem presumes a query and the user's specification of an information need. The task is then to search the particular database of interest. However, it is sometimes difficult for the user to formulate such a query precisely. For example, in the case of a document search, the user may not be familiar with the vocabulary appropriate for specifying a topic of interest, or may not wish to commit himself to a particular choice of words. In a numerical database containing time series data, the user is often interested in the general trend of the data to gain a feel of the data set. Indeed, the user may not be searching for anything specific at all, but rather may wish to explore the general information content of the database.

In fact, access to information covers an entire spectrum: at one end is a narrowly specified search for a particular piece of information given some specific search keys; at the other end is a browsing session with no well defined goals, satisfying a need to learn more about the document collection. It is common for a session to move across the spectrum, from browsing to searching with a specific goal: the user starts with a partially defined goal which is gradually refined as he finds out more about the data examined. As standard information access techniques tend to emphasise the search end of the spectrum, the interface for this type of information retrieval system can be generally catered for using a text-based form fill-in style of dialogue. In contrast, interface design to support browsing is far more complex, made more difficult by the small size of the

display screen. Further, as the search for information is carried out by the user instead of the computer, the implications on the user's cognitive resources should be carefully considered.

In developing a theoretical framework for their Information Visualizer at Xerox PARC, Card, Robertson and Mackinlay (1991) make six observations about information processing systems:

- (1) [Hierarchy] Organising the parts of a system hierarchically often improves the quantity of information processed relative to processing cost.
- (2) [High cost ratios] The cost of accessing information often varies radically both because of the cost in finding it and because of the cost of assimilating it.
- (3) [Locality of reference] The processing of information exhibits locality of reference. That is, over a small time interval, references to information are not uniformly distributed throughout the corpus, but tend to be concentrated in a subset, called the working set.
- (4) [Reference clustering] Information use defines clusters of information used repeatedly to perform some task. The processing of information tends to establish locality of reference in one cluster, then jump to another cluster. Some information may appear in more than one cluster.
- (5) [Max information/cost] Information systems tend to adjust themselves to maximise (or sometimes minimise) the quantity of information processed relative to some processing cost constraint.
- (6) [Abstraction] Lower levels of an information processing system simplify and organize information, supplying higher centres with aggregated forms of information through abstraction and selective omission.

The cost of information access time is generally translated into the cost of storage devices for the information. Consequently, different systems are used for various types of information storage, ranging from RAM (tens of nS) to optical tertiary storage devices (seconds). An information access/retrieval system can then be optimised by selecting the most often accessed items with the fastest storage device, matching usage frequency with access time.

1.2 Motivation for the Research

Baecker & Buxton (1987) observe that the information revolution has brought upon us a data explosion. The information age has succeeded in making voluminous amounts of information available at our finger tips through the ease of connection and subscription to newsgroups, electronic mailing lists, databases and remote sites. Manoeuvring through these large information spaces at best requires a lot of time, skill, determination and often patience on the part of the user to sift through the available information to extract what is considered to be useful to the user.

Recently, information filtering techniques and methods have been developed to help manage this worsening situation (Stevens, 1992; Stadnyk & Kass, 1992; Foltz & Dumais, 1992; Goldberg, Nichols, Oki & Terry, 1992); however, these filtering systems are often not enough. In every transaction with a computer, the user is making decisions. The user needs the relevant information presented in the most expressive, concise and appropriate manner possible. To achieve this, the human capacity for perceiving structure and organisation, in short for comprehension, should be exploited. The human perceptual system most capable of providing a high bandwidth communication channel is vision.

The presentation and navigation of large information spaces over a relatively small display screen still remains a major challenge to the user interface designer. "The difficulty has much in common with that of trying to peruse a newspaper through a 2-column-inch sized keyhole ('How long is this article?', 'Where is the crossword?', 'What other headlines are there?', 'What page is this?'), or of attempting to locate a needed diagram or equation within a microfiched article." (Spence & Apperley, 1982). This difficulty is coupled with the advent of multi-tasking computer operating systems which are now commonly available, where users are often required to work on multiple sources of information. Their attention on the computer screen is required to be switched among a number of concurrent tasks often presented on overlapping windows. The advantages of easy access to information offered by current computer and communications technologies may therefore be adversely affected by an unsatisfactory work environment.

The Bifocal Display (Spence & Apperley, 1982) was designed to overcome this 'Where am I?' problem which is common in the presentation of large information spaces on a small display surface. Although this technique is simple in implementation and effective for displaying large information spaces, its application has often been overlooked and its potential under-exploited. The current research is motivated by the need for an interactive visualisation tool for large databases and spreadsheets, the most

common forms of information spaces on computer systems nowadays. The Bifocal Display is also considered as a possible choice for being the fundamental presentation framework of this visualisation tool.

1.3 Objectives of the Research

The principal objectives of this research are to study and characterise visualisation techniques for large databases and to propose a design of a general visualisation tool for the presentation and navigation of large information spaces on a small display surface. Implicit in this objective are the following secondary objectives:

- that the visualisation tool should optimise the use of the available display surface;
- that the presentation technique used in the tool should be suited for information systems with high information density as well as those which are large and spatial in nature.
- that the tool should support three prime functions of user interaction with a piece of data in an information system: the location of a piece of data, its interpretation, and its relation to other data.
- that the tool should be easily adapted in a multi-tasking environment and readily implemented with the currently available technology.

1.4 Approach Adopted

The following is a summary of the approach adopted in this research to achieve the objectives set out in Section 1.3:

- A taxonomy of data, tasks and presentation techniques, together with the inherent problems of task switching, is identified. The original Bifocal concept (Spence & Apperley, 1982) is extended to two-dimensional form and the implementation of a 2D-Bifocal Display of the London Underground map is described (Leung, 1989). A comparative study using an approach adapted from the multi-dimensional evaluation methodology (Burger & Apperley, 1991) has been carried out to assess the usability of the Bifocal Display and other presentation techniques (Leung, 1992; Leung, Spence & Apperley, 1995).

- A mathematical analysis of various distortion-oriented presentation techniques forms the basis of the development of a taxonomy and a conceptual model (Leung & Apperley, 1993c; Leung & Apperley, 1994).
- An analytical framework based on efficiency, expressiveness and effectiveness in facilitating a more objective assessment of presentation techniques for large data sets is presented (Leung & Apperley, 1993b).
- The design of a visualisation tool for large spreadsheets and databases is described. The tool, the InfoLens, demonstrates the effectiveness of Bifocal Display as a presentation technique for large data sets.
- The contribution of the research is examined critically and further work identified.

1.5 Outline of the Thesis

The thesis is organised in seven chapters, the order of which also reflects the chronological development of this research. Chapters 1 and 2 present the major part of the literature survey and establish the need for an effective visualisation tool for large information spaces. Chapter 3 examines the Bifocal Display and evaluates its usability as a general approach for data presentation.

In Chapter 4, a taxonomy and a conceptual model of distortion-oriented techniques are presented to show their roots and origins which help clarify the confusing nature of these techniques. A framework for the metrication of presentation techniques is described in Chapter 5 to facilitate a more objective assessment of the relative merits of different presentation systems. Chapter 6 discusses the design rationale for and provides a detailed design of, the InfoLens, a visualisation tool for large spreadsheets and databases based on the Bifocal Display.

Chapter 7 is a review chapter in which the contribution of this research is examined and further work identified.

Chapter 2

A Brief Review of Human-Computer Interaction and Graphical Presentation

"Richard Hamming observed many years ago that 'The purpose of [scientific] computing is insight, not numbers'. The goal of visualization is to leverage existing scientific methods by providing new scientific insight through visual methods."

McCormick, DeFranti & Brown, 1987

Graphical user interfaces are now ubiquitous on modern computing machines. These interfaces exploit the wide bandwidth of the human visual perceptory system which is supported by the highly developed processing capability of the brain to interpret graphical data. Indeed, effective visualisation systems match the computer's capacity to generate and present large data sets in various graphical form to optimise the information flow between the system and the user.

This chapter first examines the human-computer communication process (Section 2.1) and discusses various communications channels available to support it (Section 2.2). Section 2.3 presents an overview of graphical user interfaces and Section 2.4 provides a discussion of the techniques for presenting graphical data. Section 2.5 reviews the problems of visualising large information spaces on a small display surface and identifies the inherent presentation and navigation difficulties.

2.1 Human-Computer Communication

The way humans use and communicate with computers has changed enormously over time. Early computers were expensive, and it was important that they did not sit idle for economic reasons. Programs and data were prepared off-line and fed to the mainframe computer continuously in batches by operators, often around the clock. After the execution of a job, the computer output was returned to the user. This approach kept the computer busy, but wasted the user's time. Users of early systems needed to have a good knowledge and understanding of how the computer works and consequently the use of computers was typically in the domain of highly trained computing professionals.

The huge technological advances in the processing power of personal computers over the past fifteen years have brought about many powerful techniques and effective devices for the user to interact with the modern computing machine. Research efforts in human-computer interaction over the same period have also provided us with a much better understanding of the communicative processes which take place between the user and the machine in a real-time interactive environment. It is now widely accepted that the bottleneck in improving the usefulness of interactive systems lies not in performing the processing task itself, but in communicating requests and results between the system and the user (Jacob, Leggett, Myers & Pausch, 1993). These developments have led to new approaches to user interface design, shifting from those purely driven by the new technologies since the early days of interactive computing machines, to those involving extensive and continual user participation and involvement. The field of computer systems design is experiencing a shift in research emphasis from producing more elegant and faster algorithms towards producing more user-oriented systems (Gaines & Shaw, 1986; Norman, 1986; Borgman, 1984). The terms 'user-centred design' and 'task-oriented design' are now synonymous with modern user interface design methodologies.

As increasing attention and effort have been placed by software engineers on producing easy-to-use and easy-to-learn interfaces, interface software is becoming large and complex and typically represents a significant portion of code in an application. Bobrow, Mittal & Stefik (1986) report that 40 to 50 percent of the code and runtime memory of artificial intelligence applications are devoted to interface aspects. Smith (1986) observes that whilst user interface software is critical to system performance, it can also represent a sizeable proportion of the cost of a project.

The creation of a good user interface requires special skills, tools and methodologies, and often the collaboration of a team of professionals with a good knowledge and understanding of human factors in computer systems. This is because the exchange of dialogue between humans and computers is far more complex than that

between humans or than that between computers. In computer-computer communication, dialogues between systems are well structured and must be pre-defined. Indeed, the International Standards Organisation has established a comprehensive reference model for Open Systems Interconnection (OSI) to facilitate the exchange of data among heterogeneous/homogenous computer systems linked together, often over long distances, by complex communications networks (ISO, 1982). The hierarchical nature of this now well known seven layer model has made it easy for the engineer to adopt a top-down approach to designing computer systems for the exchange of data in a controlled and orderly manner. A further advantage of this structured model is that it facilitates easy identification of communication faults, when they arise, within the network.

Typically, interactive human-human communication is primarily carried out over the audio channel. The exchange of dialogue is error prone, as the meanings of a dialogue depend not only upon the literal meaning of the words themselves, but also upon the context in which they are communicated and the recipient's knowledge of language and the world generally (Booth, 1989). Whilst the verbal communicative process between humans is highly complex and does sometimes lead to misinterpretation, facial expressions and gestures often supplement and enhance the bandwidth for communication. Binding, Schmandt, Lantz & Arons (1990) suggest that human communication is much richer than an exchange of text or graphical images, as it employs a variety of channels such as speech, intonation, gesture and eye contact.

The difficulties with human-computer communication lie in the fact that there is a fundamental asymmetry in human-computer interaction, which is not present in computer-computer communication. Hollnagel (1983) considers that one major contributing factor is that humans, unlike machines, are not designed explicitly as parts of man-machine systems. Norman (1986) identifies the discrepancies between the psychological variables of users and the physical variables of the system as two gulfs that must be bridged: the gulf of execution and the gulf of evaluation. He suggests that the design of a user interface should aim to minimise the gaps between the user's goals and the system.

2.2 Communication Media in HCI

The growing interest in human-computer interaction in recent years has led to a great increase in our understanding of the interactive processes between the user and the machine. Researchers have developed various models in an attempt to specify these

underlying processes (Moran, 1981; Foley & van Dam, 1982; Buxton, 1983; Nielsen, 1986). These models comprise three key components: the conceptual domain, the communication domain and physical domain (Thompson, 1991). Models of the conceptual domain generally fall into two categories: those concerned with cognitive processes and those with cognitive structure. Models of the communication domain are models of interactive language. An interactive language typically consists of a set of rules defining the syntactic structure of a language for the description of the communication between the user and the computer. Models of the physical domain consist of a representation of the physical and/or behavioural characteristics of the communication channel. Nielsen (1986) proposes a seven layer protocol model for computer-human interaction which is conceptually based on, and hierarchically similar to, the ISO reference model for Open Systems Interconnection. An important aspect of this model is that physical communication is only taking place at the physical level, the lowest layer of the model. All other levels communicate with each other indirectly through the use of a set of well defined protocols. Because of the inherent asymmetry of communication, physical interaction between the user and the machine is carried out through the use of dedicated interactive input and output devices.

Despite the comprehensive range of input and output devices currently available, the means by which human-computer communication is achieved rely on the use of three human senses through the visual channel, the audio channel and the haptic channel (Baecker & Buxton, 1987). Whilst human senses can be broadly classified as near and distant, interactive systems typically involve these two types of senses to provide a richer interaction with the user. In a modern computing environment a user interacts with the computer with input devices such as a keyboard and/or a mouse through the haptic channel, while the computer generates graphical or audio (or both) output to the user to enable the user to establish and maintain an effective mental model to perform the desired tasks.

Whilst there has been relatively little work carried out on the use of the other two human perceptual faculties, smell and taste, for human-computer interaction applications, interest has increased recently in exploring these two senses in virtual reality applications to create a more complete and realistic environment (Rheingold, 1992; Kalawsky, 1993). There are a number of reasons for the lack of research interest in these two senses, especially in their use as a means of presenting quantitative information to the user. First, the underlying operation of these two sensory processes are chemical in nature and as such, their sensations are rather subjective. Second, these two human senses are often affected by external factors and conditions; for example, tastes are strongly influenced by the presence of smell. Third, whilst there has been experimentation in the

use of smell in some virtual reality systems, there is a practical problem in overcoming the persistence of 'left-over' sensation. Fourth, there are difficulties in the generation of these senses and, from the implementation point of view, the interactive device required to support these systems tends to be too intrusive to the user for practical application. Finally, experimental evidence has shown that the channel capacity of taste intensity is significantly lower than that of the visual channel (Beeb-Center, Rogers & O'Connell, 1955), making it a less useful means of representing data.

Jacob et al (1993) observe that odours are still classified in terms of many seemingly arbitrary components, rather than a single, universal basis. Consequently, it is not yet possible to synthesise an odour in the way one can synthesise a convincing graphical image of an arbitrary object by modulating beams of red, green, and blue light on the display screen.

The haptic channel is one which involves physical contact between the user and the computer. Touch is a proximate sense. It is an important medium for communication as humans have highly developed hands which can be controlled with a fine degree of accuracy. Over the years, haptic input devices such as keyboards, mice, joysticks, tablets and gesture gloves have been developed for a variety of applications to enhance the interaction with the computer. However, haptic output devices are rare. One example would be a device capable of producing output in braille. Another recent example is the Feelmouse (Penz & Tscheligi, 1993), an interaction device with force feedback to extend the base of human-computer communication from a strongly visual to multisensory information exchange.

Strictly speaking, every input device can be considered to provide output through the tactile or kinaesthetic feedback it provides to the user. The effectiveness and acceptance of a device in a particular application often depends on the quality and appropriateness of this 'feel'. In describing their touch communication systems consisting of sophisticated touch sensors and servo-mechanisms, Geyer & Wilson (1975) postulate that touch communication may allow a growing intimacy between humans and machines. It is important to note that concepts relevant to the use of the hands generally apply to control through other parts of the body. For example, foot pedals, head operated keypress pointers and tongue activate joysticks have been developed for users with physical disabilities.

The audio channel in HCI

Historically, the development of computer user interfaces has been linked to the technology of cathode ray tubes. Consequently the application of sound as a main

medium for communication between the computer and the user has been under-explored, constrained by the need for complicated and expensive hardware to generate high quality sound (Frynsinger, 1990). The advent in recent years of low cost A-to-D, D-to-A converters, memory devices, consumer-oriented digital music synthesisers and indeed efficient data compression techniques, coupled with the development of the MIDI interface (Loy, 1985), has brought sound to a growing number of PC-based software applications. Early research interests in the use of human speech as a human-computer interface were directed towards the development of intelligent and robotic systems for voice recognition and speech synthesis in the automated manufacturing environment. Applications of non-speech audio were only confined to warning signals and alarms.

More recently, experimentations on sound as a medium for the representation of statistical data have been carried out. Chambers, Mathews and Moore (1974) use multiple parameters of sound - frequency, spectral content and modulation - to encode multi-dimensional data which cannot be displayed on a conventional scatter plot. In a similar vein, Yeung (1980) presents an audible display for experimental multi-dimensional data from analytical chemistry using frequency, intensity, damping, direction, duration/repetition and rest. He further suggests that multivariate data of up to 20 dimensions can be represented using sound and that audio representation of multivariate analytical data is superior to the known visual methods. Bly (1982) combines her auditory display scheme to a visual scatterplot and also to a combined (redundant) auditory/visual representation. She provides experimental evidence to support her argument that auditory display is at least as effective as the visual display, and that the combined display outperforms them both. Mezrich, Frynsinger & Slivjanovski (1990) developed a dynamic representation employing auditory and visual components for a multivariate time-series display to facilitate decision making.

Sound is as an ideal channel of communication for the visually impaired. Various techniques using non-speech sound have been developed to convey quantitative information to this group of disadvantaged people (Lunney & Morrison 1981; Mansur, Blattner & Joy, 1985). Audio-based interfaces have also been specifically designed for the blind user. Edwards (1989) developed a word processor called Soundtrack with an auditory interface. The system incorporated auditory menus as a means of specifying user commands. Gaver (1989) proposed the SonicFinder for the Macintosh system, which was an extension of the Apple Macintosh Finder program, that uses auditory icons (Gaver, 1986). Auditory icons are caricatures of naturally occurring sounds used to complement the visual information presented on the screen. Although this system was not specifically designed for the blind, Gaver suggested that the additional audio channel for communication serves to influence the conceptual mapping that produced the model

world that had already been developed for the Finder, adding user satisfaction of with the interface. Gaver (1993) points out that sound is well suited to providing information about previous and possible interactions, indicating ongoing processes and modes which are useful for navigation and to support collaboration. He proposes the use of auditory icons which are like sound-effects for computers, allowing the user to listen to the computer as we do to the everyday world. Gaver later (1993) developed synthesis algorithms and techniques to generate a variety of flexible, realistic sounds for auditory icons.

Another class of audio-based icons are earcons. Whilst auditory icons use sound that have a semantic link with the object they represent, earcons, as defined by Blattner, Sumikawa & Greenberg (1989), are audio messages which provide information and feedback to the user about computer entities. Families of earcons can be constructed, where audio messages with meanings are derived, through modular, transformational and hierarchical structures. Jones & Furner (1989) compared user performances between earcons, auditory icons and synthetic speech. Their results showed that whilst subjects preferred earcons they were better able to associate auditory icons to commands. In a series of experiments, Brewster, Wright & Edwards (1993) attempted to discover how well earcons can be recalled and recognised. Earcons are found to be effective for communicating information in a human-computer interface. Brewster, Wright & Edwards also showed that earcons were better than an unstructured burst of sound and that timbres were more effective than simple tones.

Whilst the question of how human beings localise auditory events is the subject of an extensive body of psychophysical research, sound has been used to provide 3D spatial information with potential applications in virtual reality systems. Moore (1989) used sound to provide spatial information through a technique called spatialisation. This technique creates the subjective "locatedness" of auditory events despite the fact that sounds responsible for these percepts emanate from loudspeakers sitting at fixed locations inside a listening space. Kendall, Martens & Decker (1989) presented the first reverberation system that recreated the full spatial-temporal sound field of a natural environment. Wenzel, Wightman & Foster (1988) proposed a three-dimensional auditory display for applications where the user's situational awareness is critical, particularly when visual cues are absent. Smith, Bergeron & Grinstein (1990) described several auditory data presentation techniques, including the generation of stereophonic sound with depth and sound that appear to emanate from a two dimensional area.

More sophisticated applications of sound in the computing environment have been proposed by researchers recently. Some researchers advocate the use of sound in programming as program auralisation. DiGano, Baecker & Owen (1993) described

LogoMedia, a sound-enhanced programming environment for monitoring program behaviour. Binding et al (1990) described VOX, a novel audio and window server architecture integrating audio and graphics as a user interface.

Proponents of the use of sound in the interface argue that overly cluttered displays can lead to a "cognitive overload" that adversely affects a user's decision making performance (Ramsey & Atwood, 1980). Blattner et al (1989) cite Buxton et al's studies (1985) where scores in a video arcade drop when the sound accompanying the video games is turned off. There is also evidence to suggest that messages presented using voice seem to be assimilated with less effort than the same messages presented through visual media (Elliot, 1937; Sticht, 1969). Green & Jacob (1991) advocate that sound can provide the user with another high bandwidth input and output channel, in addition to the visual channel.

Guastello, Traut & Korienek (1989) take the view that brain lateralization theory (e.g. Perelle & Ehren, 1983) suggests that mixed modality metaphors are more meaningful than other types. The human brain contains two cerebral hemispheres: one side is dominant and contains the verbal processing centre, and the other side is nondominant, and contains spatial processing sites. The parallel processing theory of cognition (Egeth, Jonides & Wall, 1972; Lachman, Lachman & Butterfield, 1979) also supports the view that, when a human perceives a stimulus of mixed verbal and visual context, both sides of the cerebrum process the data simultaneously. Reaction time is faster when the verbal and pictorial stimulus elements are compatible with each other, rather than conflictual (Jensen & Rohwer, 1966). Brewster et al (1993) consider that having redundant information gives the user two chances of identifying the data; if they cannot remember what an icon looks like they may be able to remember what it sounds like.

Monk (1986) suggests that sound can be used to present information otherwise unavailable on a visual display, for example mode information or information that is hard to discern visually, such as multi-dimensional numerical data. Further, whilst the foveal area of the retina subtends an angle of only two degrees around the point of fixation, sound, on the other hand, can be heard from 360 degrees without the need to concentrate on an output device, thus providing greater flexibility. Sound is also good at capturing a user's attention whilst he or she is performing another task.

Nielsen (1993) considers that interface elements such as sound can add to the richness of the dialogue and thus provide additional cues to the user without adding to the complexity of the primary interaction. Auditory icons remain in the background as long as no exceptional cases are encountered.

Despite the advantages of sound as a means of conveying information in the human-computer interface, there are some fundamental problems with it. The first and perhaps the most important feature of audio communication is the serial nature of sound. An audio menu for example must be presented serially, item by item, and the user must be attentive during its presentation to select an item. If the user misses a menu item, the audio menu will have to be replayed. This could be a problem if the number of items in the menu is large. In the case of speech communication, speech may not be sped up more than one order of magnitude without losing much intelligibility (Binding et al, 1990).

Nielsen & Schaefer (1993) found that even though the sound effects seemed enjoyable to several younger interface analysts, the older users (between 70-75 years) testing a drawing program with sound effects did not find the program more enjoyable than those testing it in a silent mode. Also the older test users found the interface more difficult to use when they were exposed to the sounds, possibly because they were overwhelmed by the multi-media effects.

Whilst sound offers some attractive features as an important component of the human-computer interface, the use of sound alone will not be appropriate in many applications, especially in the presentation of large data sets. The visual channel is a far more effective means of communication, as the high bandwidth nature of this channel facilitates speedy information retrieval and comprehension.

Visual communication and graphical user interfaces

Visual communication has a long history with the earliest writing system, essentially pictographic in nature, evolving into systems such as ancient Egyptian hieroglyphs. Today the main vehicle for delivery of information from a computer to a human being is the visual channel. Whilst the computational power of computers has improved at a phenomenal rate since the early days of computing systems, it is interesting to note that visual communication has always been the main output channel of the computing machine. With the advent of the cathode ray tube, computer output progressed from the slow, noisy teletype machines to the quiet monochrome video display unit. Later advances in electronics technology enhanced the monochrome terminal by the addition of graphics capabilities, enabling diagrams and charts to be presented on the computer screen. Then came the huge progress made in VLSI and memory chips which contributed much to the affordability and availability of colour display systems. With the proliferation of personal computing systems in the eighties, users were ever demanding higher resolution and higher speed display systems.

Nowadays, the graphics capabilities of the personal computer system can generally support high quality animation applications.

Effective human-computer interaction requires the presentation of information so that the eye and brain can work together to see what the presenter intends to be seen. The visual sensations reaching the eye are translated into perceptual experience by the brain through processes such as pattern recognition. Psychophysicists have long been interested in how the human visual perceptual system works. Their research efforts over the years have contributed to a much better understanding of the effects of luminance (Burns, Smith, Pokorny & Elsner, 1982), contrast (Patel, 1966; van Nes & Bouman, 1967), flicker (Kelly, 1961; Farrell, Casson, Haynie & Benson, 1988), motion, colour (Christ, 1975, 1984; Murch, 1984; Walraven, 1985; Davidoff, 1987), display size (Travis, 1990), and anti-alias effects (Booth, Bryden, Cowan, Morgan & Plante, 1987; Hewitt, Kennedy & Scrivener, 1989).

Human beings maintain a strongly spatial view of their surroundings. This spatial view is adequately supported by our visual system; for the visually handicapped, the sense of space is mediated by acoustic or tactile modalities. Visual communication at the human-computer interface can be broadly classified into systems which are application specific and those which are not. The latter category of interfaces supports the general operation of the computing environment and it is typically closely related to the dialogue style. The application specific interfaces, on the other hand, are typically concerned with presenting information of interest to or requested by the user.

2.3 Graphical User Interfaces

The development of computer user interfaces has been closely linked to that of the video display unit. In the early days of teletype systems and monochrome displays, user interfaces were invariably command-based where user interaction with the machine took place at the keyboard. Interaction with these types of interfaces could sometimes be very frustrating even for experienced users. The availability of colour graphics capabilities on the display screen, coupled with the advent of interactive devices such as mice, joysticks and tablets, has shifted the focus from the keyboard to the display screen in the human-computer interface design. The popularity of personal computer systems has also influenced user interface design. Emphasis has increasingly been focused on producing interfaces which are primarily targeted at novice users and aim to provide the user with a positive feeling of control and mastery of the system. Shneiderman (1983) coined the term Direct Manipulation to describe systems which have visible interface

objects and actions of interest, rapid reversible incremental actions and replacement of complex command language syntax by direct manipulation of the object of interest.

The advent of Window, Icon, Menu and Pointing-device (WIMP) interfaces has evolved from the pioneer work at Xerox Palo Alto Research Centre on the Star system (Smith, Irby, Kimball & Verplank, 1982). Nowadays, the desktop metaphor is synonymous with WIMP-based and WYSIWYG (What You See Is What You Get) interfaces. The operation of a WIMP interface is clear and unambiguous, reducing the user's cognitive load and physical interaction with the keyboard. Objects (files and programs) within the system are hierarchically arranged and represented by icons in a window. A window may act as a parent to other windows ('children') which inherit the basic operational characteristics of their parents. All windows are situated on a desktop area which represents the display surface of the monitor. Several different windows may be open at a particular point in time, and windows may be moved, resized and closed. Objects may be activated by selecting with a pointing device, typically a mouse.

The development of the Apple Macintosh system and the Microsoft Windows environment has contributed to the standardisation of user interfaces. Despite the large number of computer software applications available in the PC market, their visual appearances are becoming increasingly similar. One advantage of this familiar appearance is that each system's behaviour may be more predictable and hence encourage users to explore the functionalities of new software packages.

Visual communication plays an important role in the interface design. Jacob et al (1993) observe that current technology has been stronger in the computer-to-user direction than user-to-computer, with the bandwidth from the computer to the user far greater than that from the user to the computer. The capacity for a high volume of data to be represented graphically, coupled with the human's perceptual capability in interpreting information, has made the visual channel the ideal medium for communication from the computer to the user. In his research into multi-level statistical maps, DesJardins (1982) identifies three important aspects of graphic communication: speed, perception and comprehension. He considers that the average human comprehension rate when expressed in computer terms as bits per second would be 300bps for speech, 1000bps for text and, for pictorial representations, attain speeds of 10,000 to 100,000bps. McCormick, DeFanti & Brown (1987) suggest that the gigabit bandwidth of the eye/visual cortex system permits much faster perception of geometric and spatial relationships than any other mode, making the power of supercomputers accessible. McCormick et al (1987) point out that an estimated 50% of the brain's neurons are associated with vision and that visualisation in scientific computing is to put that powerful neurological machinery to work.

Marcus (1983) is of the view that visual communication between computers and people takes place in three different phases that represent the three "faces" of the computer: outerfaces, interfaces and innerfaces. "Outerfaces are the displays of information that are the final products of computation. Interfaces are the frames of command/control and documentation that computer system users encounter. Innerfaces are the frames of command/control and documentation that computer experts confront, specifically the builders and maintainers of computer systems." He argues that computer graphics should be exploited to support the design of each of these three faces.

Windows

The desktop metaphor was introduced in the Star and Macintosh Lisa systems, and with it the popularity of WIMP interfaces increased. In windows systems, the user's screen is divided into a number of possibly overlapping rectangular areas, each of which handles a specific function or is itself a "virtual terminal". Windows allow the user to interact with more than one source of information at the same time. It is this plethora of contexts, coupled with the graphical nature of the displays and the use of interactive input devices, which give this type of interface its power. Card, Pavey and Farrell (1984) classify windows systems into four major categories (1) the familiar TTY text windows, (2) time multiplexed windows, (3) space multiplexed windows and (4) non-homogeneous windows. Research interest in windows has been focused on the differences between systems based on the overlapping window paradigm and those based on the tiled window paradigm.

As the complexity of the windows systems increases, windows managers are used to help the user monitor and control different contexts by separating them physically into different parts of one or more display screens. These windows managers are often implemented as part of a computer's operating systems. Indeed, the increasing popularity of windows has also attributed to the standardisation of the interfaces of windows manager systems such as the Microsoft Windows, the Macintosh, the X Windows (Scheifler & Gettys, 1986) and Motif. "This high level interface can also make application code more portable from one machine to another, since the same window manager procedural interface can be provided on different machines." (Myers, 1988)

Icons

Despite its relatively short history, iconic interfacing is now widespread and it represents a fundamental aspect of the new generation of interfaces. Rogers (1989) suggests that, since we live in a strongly visual and spatially organised environment,

interfaces that also use visual spatial information are more conducive to learning. Lodding (1982), an early proponent of the use of icons at the interface, classifies them into three categories: representational, abstract and arbitrary. He further argues that icons can reduce the complexity of a system and hence make it easier to learn (Lodding, 1983). This is achieved by giving an immediate impression to the user that the system is easy to use and in doing so has a positive effect on the first time user. There is quite a selection of guidelines from a variety of fields, ranging from graphics arts to computer science, available to the icons designers (Gittens, Winder & Bez, 1984; Gittens, 1986; Marcus, 1984; Marchant, 1985)

Fairchild, Meredith & Wexelbat (1989) present a formal structure for describing icons and their relations to objects, and an extension which they called automatic icons. Icons are mappings from icon space, which deals with representational properties, to object space, which deals with computational objects. Automatic icons serve as icon generators, generating icons based on the properties of the object and the mapping between the object and the image. This provides the system designers with more power and flexibility in the construction.

There appears to be quite consistent empirical evidence to support the use of icons at the user interface. Guastello, Traut & Korienek (1989) reported that mixed modality (textual and pictorial) metaphors are rated as more meaningful than icons that utilise verbal or pictorial elements only. In their experiment to compare the usability of menu items constructed of text alone, icons alone, and text and icons together, Kacmar and Carey (1991) also concluded that menus constructed of a mixed format (text and icons) result in smallest number of incorrect choices by users without any significant difference in the time they take to make a selection. In their study of videotex choice pages, Muter and Mayson (1986) reported that whilst icon-like graphics had no effect on the users' response time, their error rate in the graphics condition was half that measured in the text only condition.

In his study of the memorability of icons in an information retrieval task, Lansdale (1988) reports no exceptional levels of recall. He suggests, however, that icons may be useful in enhancing and supporting the search process by rapidly limiting the number of documents through which a user is asked to search. Lansdale, Simpson & Stroud (1990) compared the use of words and icons as external memory aids in an information retrieval task. Their results indicated strongly that recall was higher when subjects made their own selection of enriching attributes as opposed to having them selected for them. When comparing words and icons, they found no evidence that the modalities of the enrichers were a significant factor in recall. Recall performance seems

to be primarily related to the 'semantic fit' of the documents and the attributes selected to enrich them.

Variations and enhancements of conventional icons have been considered by a number of researchers. Henry & Hudson (1990) describe the multi-dimensional icons which appear as a cube on a two and a half dimensional display surface. These icons allow several different icons representing views of an object, but occupy a fraction of the screen space which would be required to display all the icons individually. Nielsen (1990) considers the use of miniatures and suggests that the advantage of miniatures over icons is that they can be constructed automatically from the primary information to which they refer, whereas icons have to be designed manually by a graphic artist. He compares users' performance with miniatures and icons, but his results is not in favour of either. However, he recommends that the choice between miniatures and icons in a given user interface should be made on the basis of other design considerations. Everything else being equal, icons are preferred.

Baecker, Small & Mander (1991) propose a new generation of animated icons to represent complete applications or functions within an application. This type of icon serves to clarify the meaning of each icon, demonstrates its capabilities, and even explains its method of use.

Icons have proven to be an indispensable ingredient of a human-computer interface. It is envisaged that the next generation of animated icons will be augmented by an audio interface, providing a richer interaction experience for the user.

Menus

In computer terminology, a menu is a list with a limited number of options, usually words or short phrases. Shneiderman (1986) argues that menu systems are attractive because they can eliminate training and memorisation of complex command sequences. Menu applications range from trivial choices between two items to complex videotex systems involving hundreds of thousands of screens.

Based on functionality, menus can be classified into binary menus involving a choice of two items; multiple item menus; multiple selection menus, where more than one item may be selected; and extended menus, where sublists of menus are arranged in hierarchical layers. Pop-up and pull-down menus which appear on the screen in response to an activation of a pointing device are the most common types.

There has been a good body of empirical studies evaluating user performance using various tree-structure menus (Miller, 1981; Dray, Odgen & Vestewig, 1981;

Kiger, 1984; Landauer & Nachbar, 1985; Sisson, Parkinson & Snowberry, 1986). Results tend to suggest a general preference for broad, shallow trees rather than deep, narrow ones. Norman & Chin (1988) classify tree menus into constant, decreasing, increasing, convex and concave, based on the shape of the structure. They conclude that the concave menu is superior when the user is searching for scenario targets and the increasing menu is slightly superior for explicit targets. Pierce, Sisson & Parkinson (1992) propose a criterion model that accounts for variation in search strategies and response accuracy in a computer menu search task. The model considers three factors:

- (1) the user perceived relationship among target items sought and menu alternatives available for selection;
- (2) the number of alternatives available for selection; and
- (3) the probability of an omission situation where the target item is not subsumed under any of the alternatives available for selection.

Menu systems are an essential component of a modern graphical user interface. They are often used in situations where pictorial representation of objects or functions are difficult or impossible.

Pointing devices

From an early age, infants interact with their surroundings and develop useful eye-hand coordination skills. This early training has prepared them to engage in increasingly complex physical activities. It is not surprising that designs of human-computer interfaces have exploited such well-learned skills. Interactive input devices and visual displays must therefore be considered an integral part of the interface. Indeed, the use of interfaces incorporating icons, windows, and, to a lesser extent, menus would be inconvenient and possibly difficult without an effective pointing device such as a mouse. The basic functions required of pointing devices in a modern computing environment include pointing, selection, dragging and tracking.

2.4 Graphical Presentation of Data

In the context of visual communication, information display formats therefore have a direct influence on this sense of space, which in turn affect our comprehension. The use of graphics has been studied by researchers in various fields and design guidelines on the effective use of charts, diagrams and graphical displays are available (Morse, 1979; Wainer, 1984; Kosslyn, 1989; Gillan, 1993). There has also been a

variety of research into textual presentation of tabulated information on reaction time (Hicks, 1952; Wright, 1977) and the effects of table formats (Coffey, 1961; Wright & Fox, 1970; Bartram, 1980; Sprent, Crawshaw & Bartram, 1983).

Graphics vs Textual Displays of Data

Fienberg (1979) suggests that humans assimilate information more readily when it is presented in pictorial form. The advantages of such visual representations compared with textual, tabular and some statistical forms have been summarised by many (Schmid, 1983; Chernoff, 1973; Feinberg, 1979; Tufte 1983, 1990; Wainer, 1984):

- they bring out hidden facts and relationships;
- they stimulate analytical thinking;
- they enable subtle changes and trends in the data to be detected;
- they create interest and maintain the attention of the viewer;
- they enable conclusions to be communicated effectively to others;
- they enable the viewer to establish a comprehensive picture of a problem that makes possible a more complete and better balanced understanding of the situation, thus providing directions for further investigation.

Despite these apparent advantages which may be offered by graphical representation of data, there appears to be considerable conflicting empirical evidence to support these claims (DeSanctis, 1984). Barfield & Robless (1989) citing the experimental studies of Chervany & Dickson (1974); Benbasat & Schroeder (1977); Lucas & Nielsen (1980); Lucas (1981); Watson & Driver (1983); Powers, Lashley, Sanchez & Shneiderman (1985); Dickson, DeSanctis and McBride (1986) and Lee & MacLachian (1986) suggest that graphical representation of data may not be effective in some decision making tasks. Davis (1989) compares user performance of various tasks with four report formats (line graph, bar chart, pie chart and table). His results indicate that no one form of presentation is best in all situations and he argues that performance with a particular form of presentation is dependent on the tasks to be undertaken. McDonald-Ross (1977) also takes the view that "No one graphic format will prove universally superior. Each format has its own domain of application". In their study on the use of graphic and tabular displays of multi-variate data, MacKay & Villarreal (1987) conclude that the relative contribution of graphic displays to decision making may vary considerably from situation to situation. They advocate the complementary use of both graphic and tabular displays.

Bertin (1983) considers that performance with an information presentation is a function of three factors: (1) the information set presented, (2) the question to be

answered and (3) the form the presentation. In his experimental study on report formats, Davis concludes (1989) that the most appropriate method of presenting financial information is dependent on the decision maker's question: different forms of presentation are most appropriate for different questions. Graphics presentations result in better performance only when they provide specific visual cues which aid in the answering of a question. When a graph does not provide relevant visual cues, performance is best with a tabular presentation. Hitt, Schultz, Christner, Ray & Coffey (1961) suggest that user performance P may be expressed as a function of a set of seven variables: M , methods of presentation; I , type of information displayed; D , density of information; C , complexity of information; T , tasks to be performed; O , characteristics of the user; and E , external environmental factors. That is,

$$P = f(M, I, D, C, T, O, E)$$

In their research into sentential and diagrammatic representations of information, Larkin and Simon (1987) advocate that when two representations are informationally equivalent, their computational efficiency depends on the information processing operators that act on them. They conclude that:

"The advantages of diagrams, in our view, are computational. That is diagrams can be better representations not because they contain more information, but because the indexing of this information can support extremely useful and efficient computational processes. But this means that diagrams are useful only to those who know the appropriate computational processes for taking advantage of them. Furthermore, a problem solver often also needs the knowledge of how to construct a 'good' diagram that lets him take advantage of the virtues we have discussed."

Frameworks for predicting user performance on graph perception have been proposed by various researchers. In accounting for the results of experiments on comparison judgement with various graphics display formats, Simkin and Hastie (1987) consider four elementary information processes are: anchoring, scanning projection, superposition and detection operators. They suggest that anchoring is the key process for proportion and comparison judgement. Gillan (1993) describes the Mixed Arithmetic-Perceptual (MA-P) Model consisting of five component process which underlie graphic perception: searching, encoding, arithmetic operation, spatial comparison and responding. He modifies Tufte's (1983) notion of data ink ratio to the hypothesis that "the graph that will produce faster and more accurate responding will be one in which the ink helps the user search, encode, and compare (in other words, that maximises the Search, Encode, Compare-Ink ratio). In addition, graphs that reduce the

number of arithmetic operations - as a stacked bar graph reduces the need for mentally adding values - will be more effective in tasks that require those operations."

Presenting multi-dimensional data

A special class of images used increasingly in computer-generated displays is those portraying quantitative data, geographical data, and complex symbolic relationships. This is done by encoding and interpreting the data and relationships in a chart, graph, map or diagram. The use of quantitative graphics has a long history dating back to 3800 B.C. with the oldest known map of Northern Mesopotamia carved on clay tablet (Beniger and Robyn, 1978). Statistical graphics, beginning with simple tables and plots, had been well established for more than 200 years. Today, quantitative graphics with the support of powerful computing machines are reemerging as an important statistical tool with a wide range of applications. Human perception of statistical graphs, maps and charts are an important area of research for the statistician.

One of the most challenging tasks confronting the statistician is the display of multivariate data with more than three dimensions. Over the years, a variety of novel graphical representation techniques, using glyphs (Anderson, 1960), stars (Goldwyn, Friedman & Siegel, 1971), harmonic functions (Andrews, 1972), trees and castles (Kleiner and Hartigan, 1981), have been invented to represent high-order multi-dimensional data. Chernoff (1973) argues that because humans are good at recognising faces and extracting essential features from them, faces are most suited for representing multi-variate scientific data. Whilst he suggests that the facial features in a cartoon face can be used to encode a point in a 18 dimensional space, he used six features to represent his 88 geological specimens. He successfully demonstrates that these cartoon faces make it easy for the human mind to grasp many of the essential regularities and irregularities present in the data. Flury and Riedwyl (1981) extend the Chernoff faces and consider the use of more human-like, asymmetric faces to encode 36 representable variables.

Over the years, researchers have performed a wide range of experiments applying these computer-generated faces to a variety of application domains with varying degrees of success (Jacob, Egeth & Bevan, 1976; Moriarity, 1979, Stock & Watson, 1984; Brown, 1985; De Soete, 1986; MacKay & Villarreal, 1987). Researchers have identified three areas of potential difficulty with the use of these faces to represent multi-dimensional data (Huff, Mahajan & Black, 1981). First, the relative importance of certain variables may be inadvertently exaggerated because of the facial features to which they have been assigned. Brown (1985) considers that the mouth feature has a dominant influence on perception, demanding more attention from the viewer than the other features, while Oda & Kato (1993) find face shape, eyebrow tilt, and eye shapes are

more salient than others. Second, the look of a face may evoke a certain feeling. In their experiment comparing user performance on various displays, Jacob, Egeth & Bevan (1976) note that "the subjects' reports also indicated that they remembered the correctly oriented faces by means of a single term or idea, such as "happy", "glum", or "mean", while for all other stimulus types they reported remembering individual features or characteristics and were unable to integrate them into a single term." Third, in the data encoding process an extreme value in the data set would compress the range of values for other observations.

Naveh-Benjamin & Pachella (1982) believe that the salience of irrelevant information and the relationships between relevant and irrelevant information, rather than the amount of irrelevant information, are crucial factors in determining the potential for perceptual interference when using this type of facial display.

Wainer and Francolini suggest (1980) that graphic understanding takes place on three levels: (1) the elementary level - translating the retinal variable back to the quantitative component; (2) the immediate level - relating trends seen in the retinal variable to some other informational component; and (3) the superior level - comparing the entire structure of one component to that of another.

2.5 Review

The ability for a human to interact with a large amount of information on a small display screen is constrained by the human-computer interface on various fronts. First, in a typical work environment the user needs to switch tasks to achieve higher level goals; the small display area of the computer monitor often limits the number of windows which can be displayed in full view. Second, when the user interacts with a large information space, there lies the difficulty of performing the tasks of locating, interpreting and relating to other data within the user's workspace. In cases where the user does not have a well defined goal at the outset, the search for data is even more time consuming. Indeed, it has been argued that the time taken to retrieve information from a large information space is largely dependent on the ability of the user to locate and comprehend the data as the speed of computer searches improve with better algorithms and fast storage elements.

Visualisation techniques have an important role to play to overcome the presentation and navigation problems associated with the human interaction of large information spaces. This research focuses on the development of an effective visualising tool to locate and comprehend the data within a large information space on a small

display surface. The Bifocal Display is critically examined in Chapter 3 as an effective presentation technique for such an environment.

Chapter 3

The Bifocal Display

"Humans are better at processing graphical rather than numerical information and displays; computers are just the opposite."

Kasanen, Ostermark & Zeleny, 1991

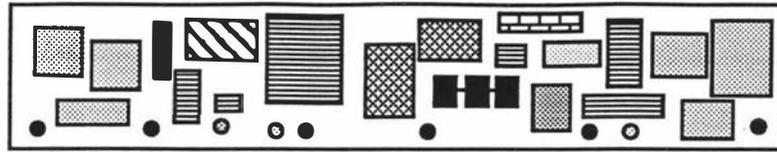
The Bifocal Display was proposed by Spence & Apperley (1982) as an effective means to present a large information space on a small display screen. This chapter, consisting of seven sections, examines the Bifocal concept in detail and presents experimental evidence in support of this technique. Section 3.1 provides a detailed description of the original Bifocal concept. Section 3.2 discusses the extension of this technique to two-dimensional applications using map-based diagrams as illustrations. To evaluate these interfaces from a usability standpoint, the multi-dimensional evaluation approach (Burger & Apperley, 1991) is considered in Section 3.3. Sections 3.4, 3.5, 3.6 describe respectively the three aspects of this comparative study: a subjective, a critical and an objective evaluation; two experiments have been conducted to collect both qualitative and quantitative data to facilitate these assessments. Finally, Section 3.7 presents a review of the Bifocal Display as an effective visualisation technique.

3.1 The Bifocal Concept

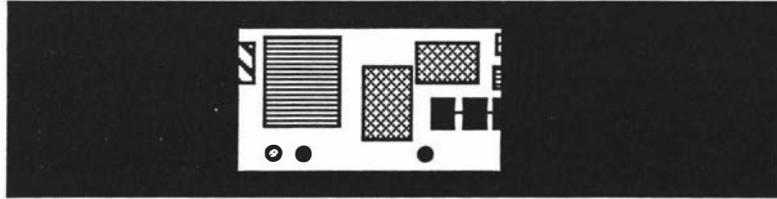
Spence & Apperley (1982) take the view that the slow acceptance of computer and other electronic techniques to assist information handling activities is related to human attitudes and behaviour rather than limitations set by technology. As the voluminous amount of information confronting the professional increases daily, there is a growing need for an effective means to handle and manage the accessible information. In describing an office environment for the professional using the technology available then, Spence & Apperley further suggest a number of novel facilities for situations where a needed item of information can be rapidly accessed and identified. One of these facilities was the Bifocal Display technique, proposed to overcome the classical "window" problem associated with viewing large databases. The essence of the Bifocal Display technique is the concurrent presentation of local detail with global context in a large information space.

Figure 3.1, an adaptation of Figure 5 of Spence & Apperley's original paper (1982), explains the basis of the Bifocal Display technique. Figure 3.1a is a representation of a data space whose area exceeds that of the available display screen, so that a conventional undistorted window view masks a large proportion of the data (Figure 3.1b). By contrast, a Bifocal presentation of this data space, as shown in Figures 3.1c and 3.1d, allows the *entire* space to be seen, with a portion shown in full detail and in context. The implementation of the Bifocal Display would involve dividing the VDU screen into three separate viewports which serves to achieve two objectives. First, it permits a number of items to be displayed in the central region with sufficient detail to be read in full. Second, at the same time the two outer 'demagnified' regions provide adequate detail of the entire remaining content of the information space.

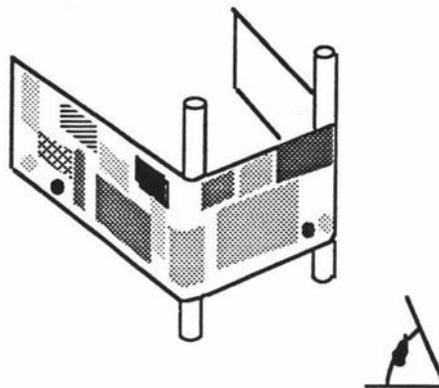
Spence & Apperley (1982) used two examples, an electronic diary and a database of journal articles, to illustrate how the Bifocal Display concept can be applied to an interactive interface. Figure 3.2 (adapted from Figure 6 of their paper) shows a display of a Bifocal diary; the two outer regions present the month strips providing the user with a global context, and the central region the day tiles of the month of interest (December) where the user can examine their contents in detail. In an interactive application, two scrolling modes are suggested; the horizontal scrolling movement updates the content of the month to be displayed while the vertical scrolling movement controls the presentation of the current week in the focus display area.



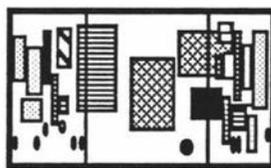
(a)



(b)



(c)



(d)

Figure 3.1 The display of a two dimensional data space; (a) the original data space, (b) a scrolled display which inevitably introduces masking, (c) the basis for a 1-D distorted view of the space, and (d) a computer generated version of this 1-D distorted view.

A U G	S E P	O C T	N O V	D E C	DECEMBER 1980					D E C	J A N	F E B	M A R	A P R	
					M 07	IEE MEETING LECTURE 3.00									
					TU 08										
					W 09	SET UP OFFICE									
					TH 10	RECORD VIDEO									
					F 11	LECTURES END									
					SA 12										
					SU 13										
1980							1981								

Figure 3.2 An electronic diary as it appears on the Bifocal Display, with the current week in the central region.

Figure 3.3 (adapted from Figures 8 and 9 of Spence & Apperley, 1982) illustrates how an article may be located involving access to information stored in various levels of a database. Consider the user is looking for an article which resides in his library of databases. The user selects an icon representing the desired journal, *IEEE Transactions on Circuits and Systems*. Figure 3.3a shows the initial Bifocal representation of the annual volumes of this journal displayed in the outer regions* with the monthly issues displayed in the central region. Colour tags and the initial letters of the author's name in the central region were also implemented to facilitate speedy visual scans and searches. Figure 3.3b shows the display of the issue of the journal which has been selected by the user. A lower layer of information is now unveiled with the selected issue of the Transactions presented in detail in the central region while the displaced months are represented in an abstract form in the outer regions.

* Spence and Apperley proposed that the detailed view of the Bifocal Display should be presented in the middle of the screen. In their original illustrations, they considered the journal series up to the year 1980. Consequently, the right hand side of the outer regions in Figure 3.3a is presented as blank.

				IEEE TR/NS ON CCTS AND SYSTEMS 1980							
1	1	1	1	January							
9	9	9	9	February							
7	7	7	7	March							
				April							
				May							
				June							
				July							
				August							
				September							
				October							
				November							
				December							

(a)

				IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS JULY 1977							
1	1	1	1	1. Topological criteria for establishing uniqueness of solutions to the DC equation of transistor networks, by Richard O. Nielsen and Alan N. Willson, Jr.	1	1	1	1			
9	9	9	9	2. The simplicial approximation approach to design centering, by Stephen W. Director and Gary D. Hachtel.	9	9	9	9			
7	7	7	7	3. A 2-D FIR filter structure derived from the Chebyshev recursion, by James H. McClellan and David K. Chan.	7	7	7	8			
4	5	6	7	4. Approximation of two-variable filter specifications in analog domain, S. Chakrabati, B.B. Bhattacharyya and M.N.S. Swamy.	7	8	9	0			
				5. Transient responses of distributed amplifiers using the m-derived filter sections, Wai-Kai Chen and Hon-Wah To.							
				6. Circuit theory analysis and synthesis of marked graphics, Tadao Murata.							

(b)

Figure 3.3 Locating a journal article with the Bifocal Display. (a) The initial Bifocal representation of the IEEE Transactions on Circuits and Systems journal. (b) Zooming in on one issue of the Transactions caused the displaced months to be represented in the outer regions (1977 on either side of the centre).

Another key concept mentioned in Spence & Apperley's paper is the use of graphical techniques in data representation, especially in the outer regions of the Bifocal Display; colour, shape tags and initial letters may be deployed to indicate important attributes such as number, size, urgency, nature and origin of the individual items displayed. Spence & Apperley (1982, p.49) emphasised that "the representation of an item in the outer regions of the display should *not* merely be a demagnified version of its central region representation, but a representation more appropriate to the lower resolution of these regions". This consideration brings about two side benefits. First, the concept of information levels, as presented visually in different levels of representation, would help the user maintain and reinforce a mental model of the hierarchical structure within the information space under consideration. Second, low resolution representation could simplify the implementation of the outer regions of the Bifocal Display as reduced system resources, such as memory and computation time, are needed (Apperley, Tzavaras & Spence, 1982).

Spence & Apperley (1982, p.53) conclude that the key advantages of the Bifocal Display is that it "presents a solution to the difficult problem of the blinkering effect of windowing, by providing a useful level of detail, of the entire context of an item of information while simultaneously providing a detailed view of that item."

To illustrate how the Bifocal Display may be extended to a two-dimensional form and to information spaces which are inherently spatial in nature, the following section describes an application of this technique to topological maps as an effective visual interface to an intelligent real time information system.

3.2 Applying Bifocal Displays to Topological Maps

Topological maps have long been used for the representation of transport and communication networks. These networks tend to be complex and, generally, their conventional representation is physically large compared with the size of a display screen. For example, although the official London Underground pocket map measures only about 9" x 6", a screen display area of 36" x 24" would probably be required to replicate the map with the same degree of detail if a typical high resolution display were employed; this is due to the fact that print resolution is much better than that of a display screen.

Because of these technological limitations, the display of topological maps on a computer screen is severely constrained by two aspects of human-computer interaction, namely presentation and navigation. The former relates to difficulties in the computer-to-human transmission of data, while the latter is characterised by cognitive difficulties involved in interpreting that data. The combined problem, which is common in large scale information systems, can be described as the "Where am I?" problem. These two constraints can be ameliorated in one of two ways. The first is to display only a small section of the map at a time; however, since little context can be displayed, this makes navigating around the map a daunting task for the user. The situation is analogous to the task of trying to read, through a hole which is one column wide and two inches high, a newspaper which has been pasted to the wall. The other technique is to uniformly scale the entire map onto the display screen, resulting in significant loss of detail.

A number of presentation techniques for topological networks have been proposed, broadly classified here as either distortion or non-distortion oriented (Leung & Apperley, 1993c). Several of these techniques are discussed in Section 3.2.2, and one, the Bifocal Display, is singled out for evaluation in comparison with other more conventional methods. However, in order to establish the requirements of such a display in the specific context of a public transport network, the characteristics of the task domain are first established.

3.2.1 The Problem or Task Domain

Whilst it is widely accepted that a good human-computer interface can bring about substantial improvements in learning time, performance, error rates and user satisfaction (Foley, Wallace & Chan, 1984), such improvements first require an understanding of the task to be performed by the user, and the characteristics of that user. The user is a person making use of an on-line information service describing a transportation system, and the task is that of using a topological map to facilitate an enquiry regarding travel information. The generality of this task description is intentional: it differs profoundly from, though it includes, the far simpler task of finding a route from A to B.

Efficient and reliable mass transit systems are essential for the operation of major modern cities. An information system, and especially one capable of incorporating frequent or temporary information updates, would improve the network's operational efficiency and the effectiveness of use by travellers. Users of such a system span a wide spectrum of expertise ranging from the naive, who have not previously encountered a computer system, to the expert, who are highly computer literate. Independently, some

users will be quite familiar with the map, whereas others will approach it for the first time. Another user characteristic concerns the local language, of which many foreign tourists will have limited or no knowledge. Most of the information system's users would be classed as discretionary users, and use would often be hurried and under the pressure of time.

This wide diversity of user characteristics suggests the following general design considerations: (1) interaction with the map display should be as natural and instinctive as possible; (2) interaction should not require knowledge of the local language; (3) symbolic representation and graphical presentation of data should be employed wherever possible in preference to text; and (4) to support the activity of map exploration (to aid mental model building as discussed below), trial and error exploration must be possible with straightforward recovery from 'errors', both intentional and unintentional.

One of the world's oldest and largest mass transit systems, the London Underground railway system comprises more than 10 different lines and over 250 stations. The design of the official London Underground map has evolved over the years and is recognised as one of the best designed topological maps. It is printed in colour and a specific colour is assigned to each line on the map. Stations are normally represented by small rectangles along the line and interchange stations by circles with the station name printed adjacent to its symbol.

During examination of and interaction with a map, a user processes the presented information and the response to interaction and thereby builds up a conceptual model of that map and the system it represents. Thus, when a foreign tourist first looks at the Underground map, he or she will immediately start to build a conceptual model. These models invariably relate to facts already known; for example, the tourist may be familiar with the Tottenham Court Road and Notting Hill Gate stations, and with the fact that they are on the Central Line, which is colour coded red on the map. When consulting the Underground map for Bond Street station the tourist might therefore establish a conceptual model that the station is about midway between Tottenham Court Road and Notting Hill Gate on the red line. As the user becomes more knowledgeable about other stations on other lines, his or her conceptual model of the Underground network grows and becomes more elaborate. The construction, possibly over a period of months or years, of this topological model, as well as its relation to geographic models of London, is an important, but certainly not the only, task which an interactive map system should support.

3.2.2 Presentation Techniques

Presentation techniques for graphical networks can be broadly classified as distortion-oriented and non-distortion-oriented.

Non-distortion-oriented presentation techniques

Two non-distortion techniques commonly used in the presentation of textual information are *scrolling* and *paging*. For the interactive map application under discussion, the technique of *scrolling*, while allowing the detailed examination of one part of the map, carries the severe disadvantage that only local context is displayed. The same disadvantage, compounded by the absence of any continuity of transition, is a characteristic of the *paging* technique. For the presentation of graphical or non-textual based information, it is suggested that a dual screen display system or a split screen system would be most applicable with large map sizes (Leung, 1989).

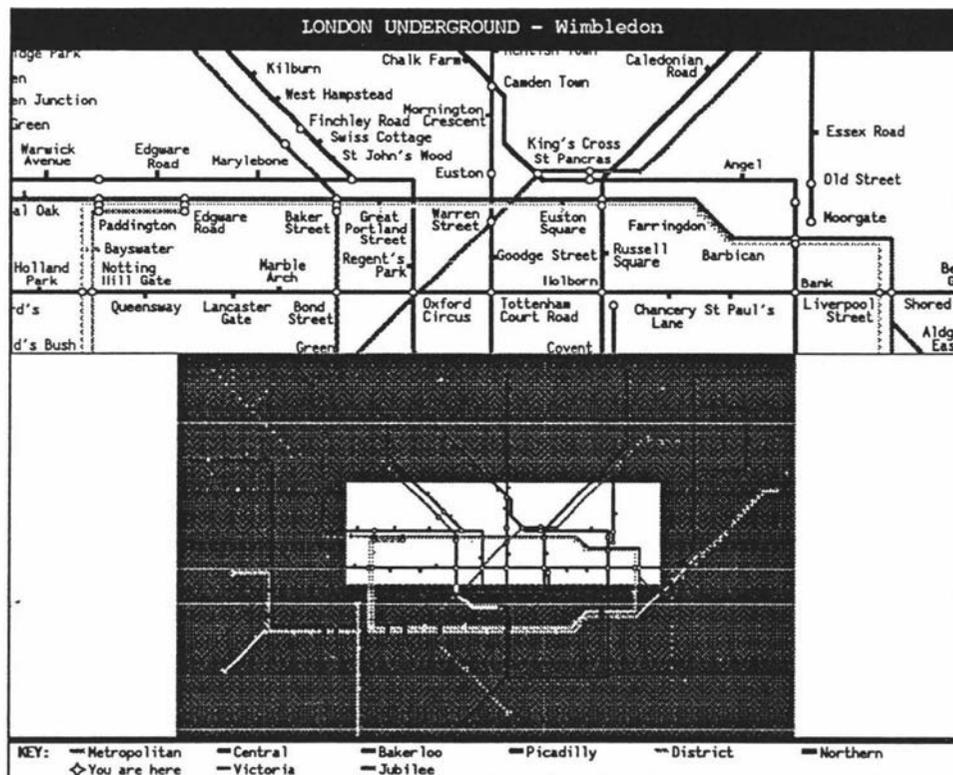


Figure 3.4 Split screen display of the London Underground map

A dual-screen display system, as the name suggests, uses two monitor screens to display the information contained in the map. One monitor is used to display, in detail, the particular section of the map of interest to the user, while the other is used to display the entire map which has, necessarily, been scaled down to fit the screen. Additionally, a highlighted area on the second screen indicates the location of that portion of the map displayed in detail, thereby providing the user with global context. With a split-screen system (Figure 3.4), the single display screen is divided into two sections, each section corresponding to one of the two screens described above.

The split-screen system is akin to an inset on a geographical map. Another similar technique is often used by television producers during the broadcast of a cricket match to enable the viewer to have a better appreciation of the match. When a run is attempted by the batsman the producer uses one camera to focus on an area covering the two batsmen and the wickets: this view will appear as a small inset on the screen. At the same time the rest of the display screen shows the overall picture of the entire cricket ground revealing the positions of the fieldsmen and the cricket ball. Since the display area is effectively halved, the split-screen system is practical only if the display monitor is large. Figure 3.4 shows a split-screen presentation of the London Underground map on a Sun workstation with 1152 x 900 resolution.

Distortion-oriented presentation techniques

Distortion-oriented presentation techniques involve the visual modification of the displayed data. There are two general approaches, (i) a group of techniques, typified by Bifocal Display (Spence & Apperley, 1982), visually modifies one part of the data space with respect to the remainder, and (ii) the fisheye view of Furnas (1986) which suppresses some parts of the information space so that the remaining parts can be seen in detail.

As this study is concerned with the presentation of maps, topological integrity is absolutely vital, and suppression of any aspect of the topology would be undesirable. It follows that only those techniques in the first of these categories are considered appropriate. The essence of these techniques is the concurrent presentation of local detail with global context. Context is indeed a very important attribute of a displayed map, since many of the tasks which they support require global as well as local awareness of details such as stations and lines. In the Bifocal Display the global context is provided at reduced magnification, in a format which allows smooth dynamic interactive positioning of the local detail without destroying spatial relationships.

The Bifocal Display

For the interactive map display a two-dimensional embodiment of the Bifocal Display concept is indicated by the need for topological continuity during movement of the detailed 'focus region' in any direction. The map display therefore involves 9 distinct regions as illustrated in Figure 3.5. The central focus region displays, in detail (including station names), a section of the map which is of particular interest. The other 8 regions are demagnified by a constant value in either x, y or x and y dimensions depending upon the position relative to the central focus region. Figure 3.6a shows a Bifocal Display of the London Underground system and Figure 3.6b a display of the Melbourne Metropolitan Railway system. As with the one-dimensional example of Figures 3.2 and 3.3, the focus region can be moved. Note that, in view of the limited display area, station names are suppressed outside the focus region. The simultaneous display of local and global context, and the smooth transition between different parts of the map, are illustrated by these examples.

Demagnification in both X and Y dimensions	Demagnification in Y dimension	Demagnification in both X and Y dimensions
Demagnification in X dimension	Central 'Focus' Region no demagnification	Demagnification in X dimension
Demagnification in both X and Y dimensions	Demagnification in Y dimension	Demagnification in both X and Y dimensions

Figure 3.5 Implementation of a two-dimensional Bifocal Display

Implementation Issues

In the implementation of a Bifocal Display as shown in Figure 3.5, the demagnification of various regions can be performed by direct scaling. Four separate bit image maps supporting the four distinct types of demagnification (demagnification in x-direction, y-direction, x-and-y-dimension and with no demagnification) can be created and stored on disk. In order to speed up system response time, these bit image files can be downloaded to system memory and the Bifocal Display then generated in real time by 'cutting and pasting' various sections of the bit image files to the display frame buffer. As the user performs a scroll operation, the 'cut and paste' operation is repeated to update the display. Furthermore, to maintain topological continuity, the position of the centre region changes as the user examines a different section of the map. To simplify the display of information in the demagnified regions, station names are suppressed in those regions. The size of the centre region of the Bifocal Display determines the amount of demagnification of the outer regions, and therefore the design must compromise between the size of the centre region and the maintenance of appropriate context. A demagnifying factor of less than 10 is recommended and the area of the centre region should not be less than one-tenth of that of the display screen.

To summarise, the application of the Bifocal Display technique to an interactive map offers the following advantages: (1) it can concurrently provide global context and local detail, (2) it allows continuous graphical and perceptual transition between different parts of the map both during interactive sessions and during periods of static display, (3) its demagnified area is entirely compatible with the use of icons to denote key aspects of the transport network, and (4) the use of a fixed de-magnification factor in the surrounding areas allows an acceptable system response time for real time applications.

Interaction techniques

Presentation techniques are not associated uniquely with a particular form of interaction. For the Bifocal Display mode of presentation the main aim of the interaction is concurrent movement of the focus region in the x and y directions, so that direct manipulation (Hutchins, Hollan & Norman, 1986) appears most appropriate. Of the more commonly used computer interactive input devices (Greenstein & Arnaut, 1987) the mouse, trackball and touch sensitive screen would appear to be suitable for this application. Regarding the interaction mechanism, a mouse or trackball would suffer from many disadvantages in a real time transport system situation including theft and vandalism in addition to being unsuitable for untrained users. Instead, a touch sensitive screen is seen to offer a natural and instinctive mechanism involving a low cognitive and training load provided that, by some means, the potential user can easily be made to

realise, first, that touch is the mode of interaction and, second, where and how that touch should be applied. Such a realisation might well be achieved by arranging, during periods of non-use, for a continuous animated demonstration involving the image of a hand. Shneiderman (1989) suggests that the prime advantages of simplicity, speed and durability make touch screens attractive for applications in public access information systems.

3.2.2 Summary

This section has provided a description of various presentation techniques for topological maps. The Bifocal Display technique has been extended to two dimensional form for this type of interface, illustrating its suitability also for information systems whose data are spatial in nature. The following section describes an experimental study to compare various techniques to provide a better understanding of these types of interfaces from the human-computer interaction perspective.

3.3 A Comparative Study of Graphical User Interfaces for Topological Maps

A comparative evaluation of the presentation techniques described in this section will help to identify their merits and shortcomings. The main aims of this study were to uncover users' experiences and preferences with these interfaces and to measure task completion times in the performance of various tasks typically faced by users of such systems. More specifically, the objectives were:

- to observe how users used these interfaces and what difficulties were encountered
- to uncover what station name searching strategies were used on various interfaces
- to ascertain the order in which subjects preferred to use the interfaces
- to find out if there was any significant difference in users' performance of various tasks with the interfaces

3.3.1 An Integrated Approach to Interface Evaluation

Burger & Apperley (1991) consider a list of problems associated with current interface evaluation techniques and propose a multi-dimensional evaluation approach which entails three major evaluation types, namely, critical evaluation, subjective evaluation and objective evaluation. They argue that "using one, or even two, of the techniques in isolation can result in a biased or incomplete view of the interface. Some aspects of the interface will be highlighted by one technique and not by the others and it is therefore essential that none of the three be left out in the evaluation process."

This integrated approach is particularly applicable to graphical user interface evaluation as complex human behaviour exhibited in the course of user interaction with this type of interface cannot be simply summarised by a set of numbers in terms of task completion times and error counts. In order to get a richer picture of user interaction and a more accurate and reliable basis to compare these interfaces, this integrated evaluation approach has been adopted.

In this study, the London Underground wall map together with four map-based interfaces implemented on a workstation were used. A detailed explanation of some of these map-based interfaces and their implementations has been discussed in Section 3.2. The following subsection describes in brief their general features and characteristics.

3.3.2 Map-based Interfaces

The five interfaces used in this experiment were, a paper wall map, Bifocal Display (point and shoot), Bifocal Display (scrolling), simple scrolling view and split screen (scrolling) systems. The fisheye view system used by Hollands et al (1989) had not been considered in this experiment as the complexity of the London Underground map would incur excessively long processing time required to generate the fisheye view on the Sun IPC Workstation; the slow response time would render the fisheye view interface unusable.

Paper Wall Map

The paper wall map, which measured 900mm x 600mm, was the official London Underground map produced by the London Regional Transport Authority. Being one of the world's oldest and largest mass transit systems, the London Underground railway system comprises more than 10 different lines and over 250 stations. The map is printed in colour, and a specific colour is assigned to each line on the map. Stations are normally represented by small rectangles along the line and interchange stations by circles.

Bifocal Display - Point and Shoot

Figure 3.6a shows an implementation of the London Underground map using this technique. With the point and shoot interface, the user moves the central focus region to another location by first positioning the cursor using a mouse to the point of interest and then clicking a mouse button. The new Bifocal image will then be presented; on a Sun SPARC IPC workstation the response time was about a quarter of a second.

Bifocal Display - Scrolling

The static presentation of the Bifocal Display is identical to the one discussed earlier. However, with a scrolling interface, the user moves the central focus area by scrolling a mouse. The system detects the direction of the mouse movement and updates the Bifocal image in real time; the amount of movement of the central focus area is directly proportional to the scrolling action on the mouse made by the user.

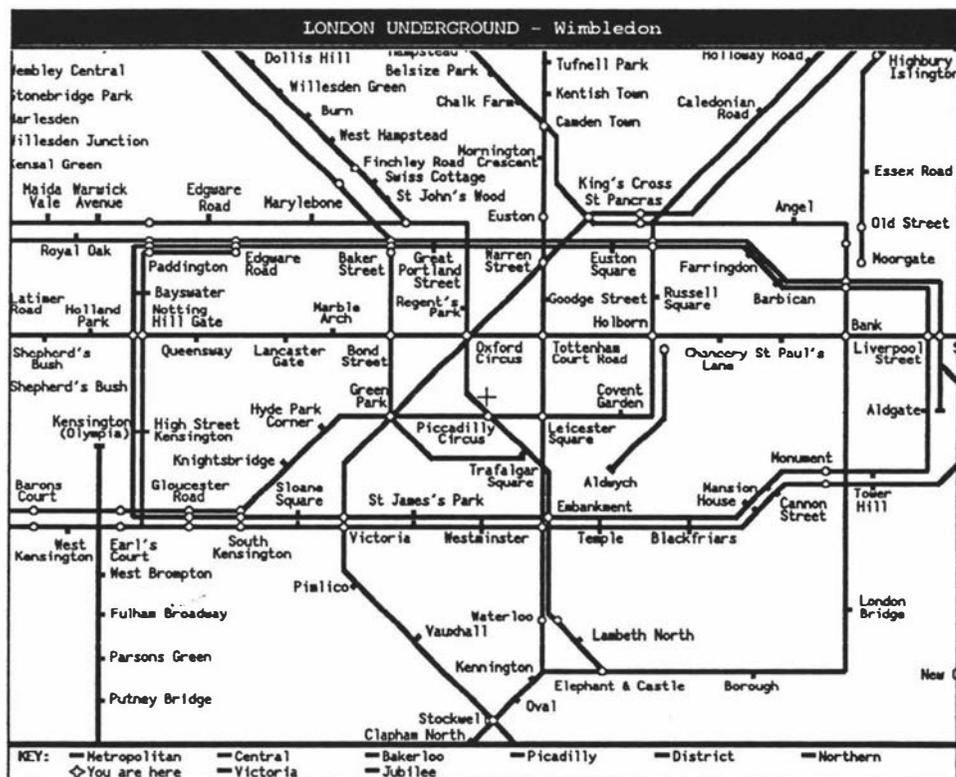


Figure 3.7 Scrolling view of the London Underground map

Simple Scrolling View

The scrolling operation for this interface is similar to that described earlier. With simple scrolling view, a section of the map will be displayed in detail at any one time. Although this interface accommodates a larger detailed display area on the screen, it provides no global information about the position of the current display in relation to the entire map. If the current display is at one extreme of the map, further scrolling in that direction will not result in a change of view. Figure 3.7 illustrates an implementation of this presentation technique.

Split Screen Display - Scrolling

The split screen display as the name suggests, partitions the display area into two sections with one section displaying a small area of the map in detail and the other a reduced size of the entire map. On the demagnified map the area which the detailed display is currently presenting is highlighted to enable the user to maintain an overall perspective of the map. This technique is akin to an inset on a geographical map. Figure 3.4 shows an implementation of this presentation technique.

As the user scrolls the mouse, the two sections of the screen will be updated in real time according to the direction of and proportional to the scroll movement.

3.4 Subjective Evaluation: Experiment 1

3.4.1 Subjects

Thirteen paid subjects participated in this experiment and they were either students or administrative staff in various departments on the Swinburne campus. The subjects represented seven nationalities (Australian, Hong Kong, Malaysian, Pakistani, Sri Lankan, Greek and Indonesian; for details see **Appendix A.6**) to simulate the mix of nationalities in overseas tourists using the London Underground system. The subjects covered a wide range of experience with computer systems and they all had had very limited or no prior knowledge of the London Underground map (**Appendix A.5**).

3.4.2 Apparatus

The graphical user interfaces had been developed on a Sun SPARC IPC colour workstation. The monitor of the workstation had a resolution of 1152 x 900 pixels and it supported a wide colour range to enable a close replica of the wall map to be presented.

An optical mouse, which was the only input device operated by the subjects, was an integral part of the workstation.

The wall map, which measured 900mm x 600mm, was the official London Underground map produced by the London Regional Transport Authority. The map was fixed onto a cardboard backing of similar size so that it could be easily placed in an upright position to allow the subject to work on it while sitting down.

A VHS video camcorder mounted on a tripod was used to record each experimental session.

3.4.3 Experimental Design

Think-aloud verbal protocols were video-recorded from thirteen subjects interacting with a number of map-based interfaces for the London Underground Map implemented on a Sun SPARC IPC workstation. The subjects performed a series of tasks on the map-based interfaces presented. While the video-recorded experimental sessions would give a detailed account of the interaction, an analysis of the verbal protocols and careful observation of the interaction might also unveil valuable information about the subjects' cognitive states and processes involved in performing these tasks. At the end of the experiment, each subject completed a short questionnaire so that their computer competency, prior knowledge of the London Underground Map and their interface preferences could be ascertained. (For details of the questionnaire see **Appendix A.4**).

The tasks involved searching for stations and planning a route using a wall map and various map-based interfaces presented on a workstation. Subjects used the following station-related information as search keys:

- (1) Station name and Position (North, South, East or West);
- (2) Station name and Proximity (to another station identified in an earlier task);
- (3) Station name and Line (colour);
- (4) Intersection (between two lines);
- (5) Station name alone.

The five tasks were tested repeatedly (using different station names for each task and for each interface) on five interfaces, namely, wall map, Bifocal Display - point and shoot, Bifocal Display - scrolling, simple scrolling view and split screen - scrolling (for the complete task lists, see **Appendix A.3**). In order to minimise the order effect, five

different test sequences on the interfaces were used. Each subject spent about an hour on the entire experiment.

3.4.4 Procedure

The experiment was conducted in a small office where the Sun SPARC station was situated. Each session was video-recorded to facilitate future data collection and analysis. At the beginning of the experiment, the subject was seated in front of the workstation and a brief introduction was given to explain the purpose of and the tasks involved in the experiment. The subject then read the introduction sheet (see **Appendix A.1**) and a five minute practice session with the Melbourne Metropolitan Railway map on the computer followed. (All the subjects were familiar with the Melbourne Metropolitan Railway system.) The purpose of this practice session was to familiarise the subject with the computer equipment and system hardware, and at the same time, to make the subject feel comfortable with verbalising their thoughts while locating a station on the interface.

When the subject was ready to start the experiment, an instruction sheet (see **Appendix A.2**) was given to the subject. At the beginning of the experiment, the subject was first presented with the London Underground wall map and the subject was required to locate six interchange stations in the central London area. The purpose of this was twofold: firstly, it provided the subject with an overall perspective of the map and secondly, it enabled the subject to establish mentally some 'anchor points' on the map to which they could refer when performing later tasks. Before a new interface was tested on a user, a brief practice session (about two minutes) was given to enable the user to get accustomed to the new system.

3.4.5 Results of Experiment 1

The experiment on the thirteen subjects was carried out over five working days. Altogether about ten hours of video recordings were made. The results from the verbal data and the questionnaire were collected and analysed. They were classified as quantitative and qualitative data.

Quantitative Data

Each interface was rated by the subjects using a Likert scale of 1 (very poor) to 6 (very good). The analysis of subjective quantitative data inherently poses an interpretation problem as the semantic difference between the subjects' interpretation of any two category descriptions is more than often not equal to the numeric distance

between the values assigned to those categories (Nielsen & Levy, 1994). A more appropriate comparative assessment of the data would be to consider their relative order of user preferences.

The raw quantitative data collected from the questionnaire is presented in **Appendix A.5**. The ratings data collected were transformed into a preference table and **Figure 3.8** shows the profile of subjects' preferences of these interfaces. Whilst the number of subjects involved in this assessment is *too* small to warrant further analysis of this data set, the preference profile suggests that the wall map and the Bifocal point & shoot were the preferred interfaces.

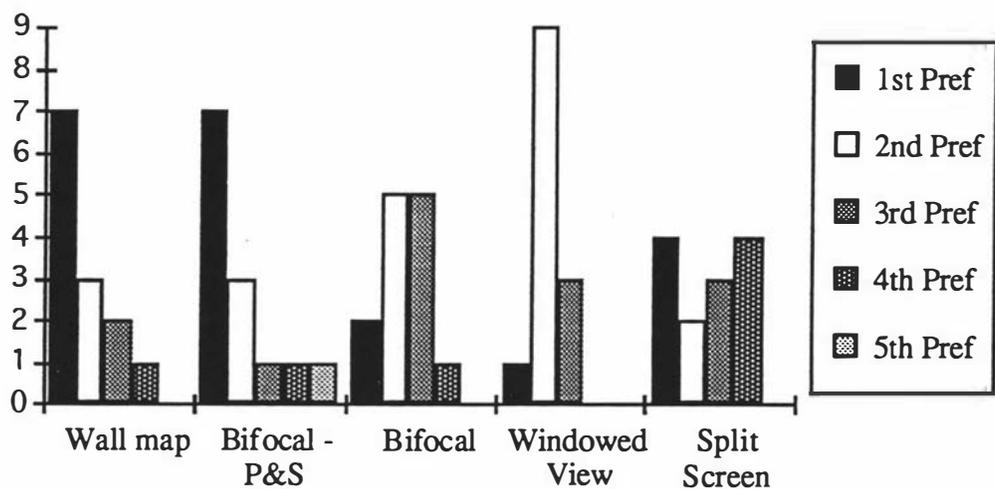


Figure 3.8 Subjects' relative preferences of the five interfaces

Qualitative Data

The recorded verbal protocols were carefully analysed and the following is a summary of qualitative data collected (**Appendix A.7** shows samples of verbal data collected from two subjects):

- There is a general problem with long station names for non-native English-speaking subjects. Subjects used various station name matching strategies, such as match by first word, by first character, by length, and by sound. Native English-speaking subjects tended to match by the first word while non-native speaking subjects used other strategies.
- Nearly all subjects were misled by station names like Acton East and Hampstead North. They intuitively assumed the directional information

contained in the station name was associated with its physical position on the entire map; for example, many subjects thought Acton East was in East London.

- With simple scrolling view and split screen interfaces, there was a tendency for subjects not to search through the current display before scrolling on to the next display area. Very often subjects missed a station in the current display that they were looking for because they did not search thoroughly before moving on.
- The way subjects used the split screen interface was fairly consistent. Subjects would first concentrate on the lower half screen to locate the highlighted window in the target area (based on the information given) and they then switched their attention to the upper half screen to search for the target station name. As subjects became more familiar with this interface, they concentrated on the upper screen and only referred to the lower screen occasionally.
- In terms of users' performances, scrolling view and split screen interfaces appeared to be superior to Bifocal interfaces in route finding and interchange station finding tasks; subjects would attempt to fit the two stations on the detailed display area to determine the route. In the case of the Bifocal interfaces if the two stations would not fit in the Bifocal window, subjects tended to move the window from the source station to the destination to confirm the route. Some subjects moved the Bifocal window to one corner to locate the interchange station or to determine the route between two stations, especially with the point and shoot interface where moving the Bifocal window to one corner could be done very quickly.
- All subjects performed all the tasks with the paper wall map fairly effectively and efficiently. Towards the end of the session all subjects were reasonably proficient with all the interfaces for the London Underground map.

3.4.6 Discussion

Verbal Data

Whilst some of the functional tasks involved in this experiment could be quite difficult (for example to find a station from the map without any additional information) the operations subjects had to perform were relatively simple; this is typical of most graphical user interfaces. In this experiment, such operations included the control of a mouse to display the area of interest and matching the station names on the display with the target station name. In the course of the interaction, the user's attention would focus on the display screen where the information was presented and received through the

visual channel. The user would then have to organise and analyse the information collected, and finally react to it by activating the hardware interface. The visual channel is bandwidth wide and information rich, and it operates in a parallel fashion. In contrast, the oral channel functions in a serial fashion. Therefore, the task of verbalising whilst interacting with a graphical user interface is very demanding, and there could be a tight bottleneck in the information flow from visual channel to the oral channel.

Of the thirteen subjects, eight were non-native English speakers. This posed an additional burden on these subjects and it compounded the verbalising problem mentioned above. There were occasions when subjects could not cope with this demanding task and kept silent altogether. One way of minimising this problem would be to ask subjects to verbalise in their native tongues and then translate their oral reports into English for subsequent analysis.

Another limitation of the verbal protocol is that it would not allow accurate measurement of time taken by the user to perform a task concurrently. The graphical data is information rich in nature, so the length of time the subject performed a task would be related to how detailed the subjects' verbalisation of their thoughts was. However, this is generally not a real constraint on the evaluation of graphical user interfaces as oral data would contain much richer information than the absolute quantitative values. The quantitative evaluation in this experiment refers to the subjective data provided by the subjects concerning their interface preferences.

Summary of Results - Subjective evaluation

Based on the qualitative results of this experiment, there is strong evidence to suggest that minimum training would be required to operate any of these interfaces as users performed all tasks adequately; in particular, subjects worked very effectively and efficiently with the wall map. Further, there is evidence to suggest that each interface has its own merits in specific task performance; the Bifocal window is superior in station-searching tasks while split screen and scrolling view interfaces are better in route-finding and interchange-station-locating tasks. It is interesting to note that although the split screen and scrolling view interfaces provided a larger display area of the map than the Bifocal window, there was a tendency for subjects not to search thoroughly on the entire display area before moving on to the next search area. In the case of the Bifocal Display interfaces, because the area of display was smaller, subjects would focus on the window and searched through it more carefully.

Based on the quantitative results of this experiment, there appears to be very little difference in terms of users' preferences between the paper wall map and the Bifocal

Display with a point and shoot interface. The preference profiles of the other three interfaces are rather mixed and it is difficult to make any conclusive comparison. It is interesting to note that the Bifocal point and shoot interface is preferred over the scrolling Bifocal Display. This may be due to the slightly longer system response time taken to generate the scrolling image with the current system.

The Bifocal Display with a point and shoot interface could be considered as a preferred interface for implementation as a front end to a real time information system. The only task the users will be required to perform on such a system, will be to locate the destination station on the display. The route and interchange information will be determined by the computer system. With the absence of a wall map, the scrolling view and split screen interfaces, on the other hand, may serve as a training aid for users to establish and refine their conceptual model of the network.

Generalisation of Results

Whilst this comparative study provides conclusive evidence to the effectiveness of the interfaces tested, further generalisation of the results should be made with caution. Firstly, the size of the map to be implemented using these techniques would have a significant impact on the choice of presentation techniques used (Leung, 1989). Secondly, the tasks to be performed by the users and the information conveyed by the topological map should be carefully considered; in the case of a topological map for a computer communications network, for example, it may serve to provide different levels of information such as system traffic loads, link capacities, etc. Thirdly, these techniques may not be readily extended to non-topological entities such as geographical maps and geographical information systems; further investigations will be required.

Finally, system response time is a major factor in the usability of a graphical user interface. Graphical user interfaces, by their very nature, consume large amounts of a system's processing power. The various presented techniques evaluated in this experiment involve the manipulation of pre-generated bitmaps stored in memory. Consequently, they do not consume much computational resources and their system response times are negligible.

3.4.7 Conclusions

Whilst the following conclusions can be drawn from this qualitative evaluation, it should be re-emphasised that other variables, such as map size and non-topological type maps, should be considered before further generalisation of the findings:

Firstly, in terms of effectiveness and efficiency, the wall map is the best in presenting topological information and providing general functionality for this map size. The Bifocal Display with a point and shoot interface is the best computer-based interface evaluated in this experiment.

Secondly, users could operate all computer-based interfaces in this experiment with minimum training and were able to perform the tasks such as locating a station on the display whether they had extra information available to them or not.

Thirdly, for the computer-based interfaces, users performed better with the Bifocal Display in searching a station without any additional information. On the other hand, they performed better with the scrolling view and split screen systems in tasks such as determining the route between two stations and locating a station intersected by two lines.

Fourthly, native-English speakers searched for station names by matching the first word while non-native-English speakers used other matching strategies such as, match by first character, by length, and by sound.

3.5 Critical Evaluation

Ravden & Johnson (1989) recommend a comprehensive checklist for the evaluation of general human-computer interfaces by "evaluators". Some of these guidelines, however, are not directly applicable to the evaluation under consideration:

In the context of display methods for large compound graphs, Misue & Sugiyama (1991) suggest five design criteria:

Detailed View: The display should enable the viewer to examine its contents in detail.

Global View: The display should provide the viewer with a global perspective to facilitate navigation.

Minimal View Switching: The display should minimise the need for switching of detailed and global views.

Context: The display should provide the viewer with adequate context to reduce potential difficulty with interpretation.

Representation of Information : The display should take into account of the nature of the information to be represented and presented; for example, in the case of map-based diagrams, preservation of topology is important.

	Wall map	Bifocal P&S	Bifocal Scrolling	Scrolling View	Split screen Scrolling
Detailed View	v. good	good	good	good	good
Global View	v. good	good	good	poor	good
Minimal view switching	v. good	good	good	n.a.	poor
Context	v. good	good	good	v. poor	good
Representation of Information	v. good	v. good	v. good	v. good	v. good

Table 3.1 A critical evaluation of the five interfaces based on five display criteria

	Wall map	Bifocal P&S	Bifocal Scrolling	Scrolling View	Split screen Scrolling
station name & position	v. good	good	good	fair	fair
station name & proximity	v. good	good	good	fair	fair
station name & line (colour)	v. good	good	good	good	good
intersection of 2 lines	v. good	fair	fair	good	good
station name alone	good	fair	fair	fair	fair

Table 3.2 A critical evaluation of the five interfaces based on tasks

The above criteria address all the important issues related to map-based interfaces and a critical evaluation of the five map-based interfaces used in the qualitative evaluation is made based on these criteria. Each interface was rated in one of the five categories: very good, good, fair, poor and very poor. Table 3.1 shows the results of this critical evaluation of these interfaces.

This evaluation shows that the wall map has been consistently rated highly, and since the representation of the information to be presented, the London Underground map, is identical, the five interfaces have been given the same 'v. good' rating. For the simple scrolling view, as no switching facilities were provided, a 'not applicable - n.a.' rating was, therefore, assigned.

At the task level, a critical evaluation of the interfaces has been made based on the ease of users' performance of the five specific tasks carried out in experiment 1. The tasks associated with each interface were similarly graded in one of the five categories: very good, good, fair, poor and very poor. Table 3.2 shows results of a critical evaluation of these interfaces.

3.6 Objective Evaluation: Experiment 2

3.6.1 Subjects

Thirty four paid subjects participated in this experiment which was conducted on the Swinburne campus. The subjects were selected from a population similar to those in experiment 1. While their experience with computers were varied, all the subjects had had no or very limited knowledge with the London Underground map.

3.6.2 Apparatus

The hardware used in this experiment was similar to that in experiment 1. A digital stop watch was used to measure task completion times, and the experiment was not video-recorded.

3.6.3 Experimental Design

In this experiment, each subject was required to perform three station-locating tasks on each of the four computer-based interfaces using the following station-related information as search keys: (1) station name only; (2) station name and some directional

information; and (3) station name and colour. The order in which the interfaces were presented to the subject was randomly generated, covering all possible permutations to minimise any order effect. Each subject completed the three tasks with one interface before moving on to the next (similar) three tasks with another interface. Presented to the subjects in the following order, the following are examples of the three tasks for each of the four interfaces:

Task 1 You have to meet a friend at **Stonebridge Park** station. Find the station.

Task 2 From the station you have just located (Stonebridge Park), move in a *south-east* direction to find **Kennington** station .

Task 3 You have to meet a friend at **Elm Park** station on the green line. Find the station.

3.6.4 Procedure

This experiment was conducted in an environment similar to that described earlier in experiment 1. A brief introduction was given to the subject to explain the purpose of and the tasks involved in the experiment. The subject then read the introduction sheet and filled out a questionnaire about their competency with computers and their knowledge of the London Underground map. Before a new computer-based interface was introduced, the subject was given a two minute practice session with the Melbourne Metropolitan Railway map to acquaint with the system hardware.

3.6.5 Results of Experiment 2

The experiment was conducted over a ten day period and subjects spent about 25 minutes to complete the experiment. Task completion time for each task was taken and recorded using a digital stop watch; twelve time measurements were made per subject (three tasks for each of the four interfaces).

A time limit of two and a half minutes (150 seconds) for each task was introduced as it was felt that if the subject could not complete a task within this time limit, frustration and other factors would impair unduly the subject's performance in subsequent tasks.

Table 3.3 shows a summary of the task completion times of the 34 subjects. For the purpose of data analysis, the uncompleted tasks were assigned a completion time of 150 seconds as it would be incorrect to treat them as missing data. Table 3.4 shows the frequencies of these uncompleted tasks.

	Measures	Bifocal Scrolling	Bifocal Point & Shoot	Split Screen Scrolling	Windowed View Scrolling
Task 1	mean	57.265s	78.471s	83.147s	84.824s
	standard dev	43.530s	50.695s	52.222s	49.835s
	min	4s	2s	3s	7s
	max	150s	150s	150s	150s
Task 2	mean	43.059s	51.294s	45.824s	48.500s
	standard dev	32.395s	37.699s	33.394s	37.289s
	min	13s	5s	4s	11s
	max	126s	129s	150s	150s
Task 3	mean	25.412s	46.088s	39.794s	27.735s
	standard dev	11.735s	35.101s	29.137s	21.653s
	min	5s	4s	5s	3s
	max	70s	150s	150s	100s

Table 3.3 A summary of task completion times in seconds of the 34 subjects in Experiment 2. The 150s entries indicate that the tasks were not completed.

	Bifocal Scrolling	Bifocal Point & Shoot	Split Screen Scrolling	Windowed View Scrolling
Task 1	2	8	7	6
Task 2	0	0	1	1
Task 3	0	1	0	0
Total	2	9	8	7

Table 3.4 A summary of the number of uncompleted tasks for each of the four interfaces

This experiment was a two factorial repeated measures design with each subject measured at each of the two-factor combinations (Interface x Task). The ANOVA model used the third order interaction as the residual error term.

Whilst no two-factor interactions were significant, Interfaces ($F_{3,198} = 4.6$, $p = 0.005$) and Tasks ($F_{2,198} = 33.58$, $p = 0.000$) were highly significant.

Using two-tailed Least Significant Difference tests, the Bifocal (scrolling) interface differs from the other three interfaces as a group ($t_{198} = 2.283$, $p = 0.023$), but there is no significant difference between these three interfaces. However, the difference in the two-tailed LSD tests is not significant at 5% using the more conservative Scheffe test.

Using the Scheffe test, all three tasks were significantly different (Tasks 2 and 3, $p < 0.05$; Tasks 1 and 2, $p < 0.001$).

3.6.6 Discussion

The quantitative results of Experiment 2 provided evidence to support that subjects performed best with the Bifocal Display with a scrolling interface when compared with the others in three station locating tasks, suggesting a scrolling Bifocal interface is better than a point & shoot Bifocal Display. In Hollands et al's study (1989), they compared user performance of a simple windowed view (scrolling) with a fisheye view (point & shoot). The introduction of this additional dimension of interaction style made their performance comparison less generalisable.

The results of experiment 2 also indicated that the variability of task completion times between interfaces was quite large. This variability probably contributed partly to the fact that the more conservative Scheffe test showed no significant difference among the four interfaces. However, it should be pointed out that the uncompleted tasks (see Table 3.4) tended to distort the true picture; in reality the 'uncompleted' tasks would take more than 150 seconds to complete although they were notionally assigned a value of 150 seconds in the data analysis. As such, the three 'poorer' interfaces with seven to nine uncompleted tasks are actually worse than they appeared when compared with the Bifocal (scrolling) interface which had only recorded two uncompleted tasks.

As expected, the difficulty of the three station locating tasks may be ranked in descending order: Task 1, Task 2 and Task 3. Task 1 involved finding a station without any additional information and subjects had to expend much effort in navigation in addition to name matching. In contrast, Task 3 where the line colour of the target station was provided was relatively easy as the subject can follow the line colour systematically to find the target station. In Task 2, information related to the general direction of the station on the map was given. This additional information though useful to the subjects, is less definitive than the line colour. Consequently, subjects had to navigate and search over a larger display area than that in Task 3.

It is important to note that an experiment based purely on objective measurements would run the risk of grossly underestimating both the complexity and range of tasks that might be attempted through use of the system, as well as the extremely diverse nature of expected users and their prior knowledge of the map and the network it represents. For example, to refer to only one of many facets of the problem being addressed, the manner in which people derive knowledge from maps (Thorndyke & Hayes-Roth, 1982) is far from straightforward, and is almost certainly influenced by their travel through the system represented by that map. Rather, in agreement with a view cogently enunciated by Carroll (1990) and widely supported, an examination of the richer picture of real use of such a system is advocated; the development of a cognitive and interaction model of the system will be of more value than experiments with simplified tasks attempting to identify which implementation is 'best' in some limited respect as such results are often difficult to generalise.

3.7 Review

This chapter has critically examined the Bifocal Display and its extension from various perspectives. Implementation issues related to the Bifocal Display has been discussed followed by an in-depth comparative study of various graphical user interfaces based on an integrated multidimensional evaluation approach. This study of map-based interfaces has provided both a quantitative, a qualitative and a critical assessment of the Bifocal Display and other presentation techniques using the London Underground map. The data collected and the analyses that followed in this study has provided strong evidence to suggest that the Bifocal Display is an effective visualisation tool also for large information spaces which are inherently spatial in nature.

Chapter 4

A Taxonomy and Conceptual Model of Distortion-Oriented Presentation Techniques

"Information, that is imperfectly acquired, is generally as imperfectly retained; and a man who has carefully investigated a printed table, finds, when done, that he has only a very faint and partial idea of what he has read and that like a figure imprinted on sand, is soon totally erased and defaced."

Playfair, 1786

4.1 Introduction

One of the common problems associated with large computer-based information systems is the relatively small window through which an information space can be viewed. This gives rise to problems (i) in locating a given item of information (navigation), (ii) in interpreting an item, and (iii) in relating it to other items, if the item cannot be seen in its full context. Various techniques have evolved for accessing large volumes of data through a limited display surface, and these can be broadly categorised as distortion-oriented and non-distortion-oriented presentations. The data itself can also be classified according to whether it is inherently graphical in nature, with implicit spatial relationships, or whether it is non-graphical, although in many cases data of this latter type can be represented in an abstract graphical form (Leung & Apperley, 1993b). Figure 4.1 shows a simple taxonomy of these techniques, with examples of each of the four types.

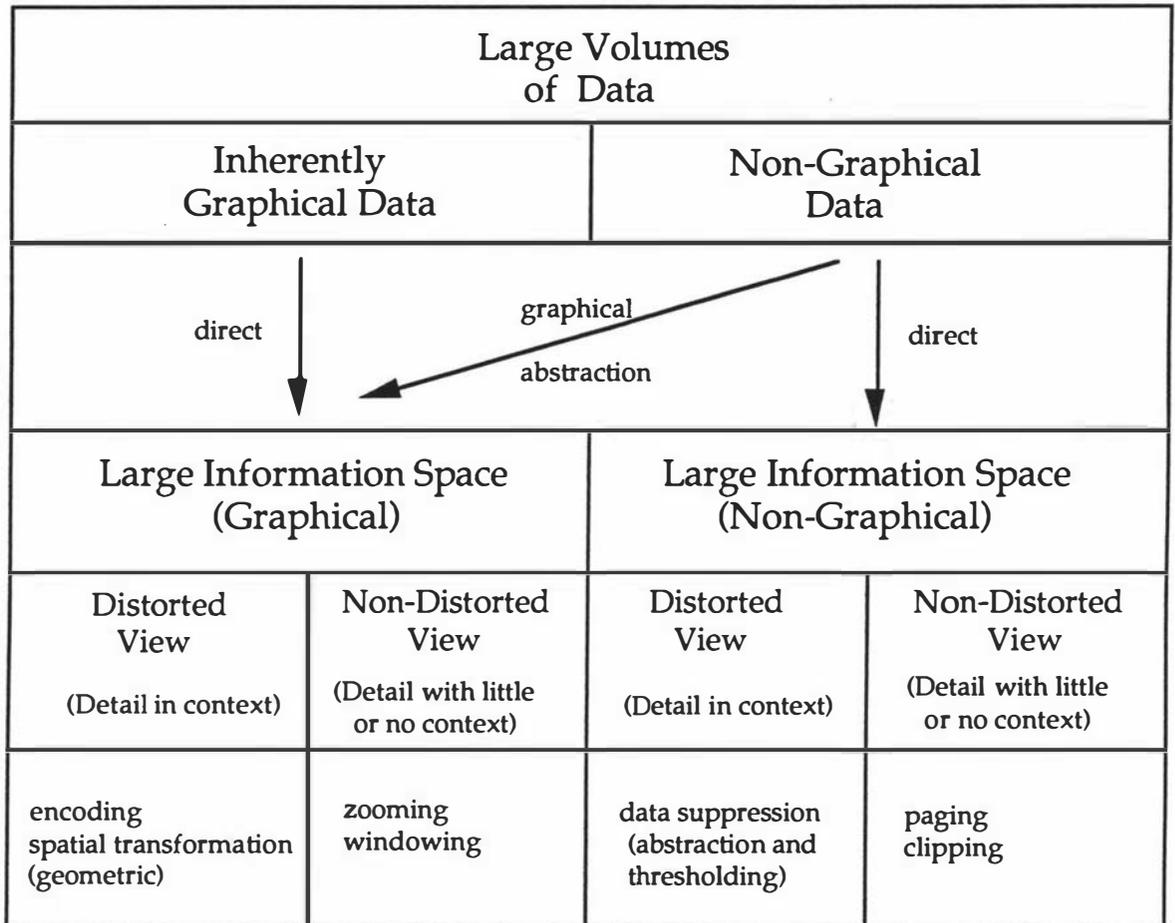


Figure 4.1 A taxonomy of presentation techniques for large graphical data spaces.

Non-distortion-oriented techniques have long been used for the presentation of textual data (Monk, Walsh & Dix, 1988; Beard & Walker, 1990) and also in a number of graphical applications (Donelson, 1978; Herot, Carling, Friedell & Framlich, 1980; Leung, 1989). The most familiar approach is to simply display a portion of the information at a time, and to allow scrolling or paging to provide access to the remainder. An alternative, and one which does enhance the ability to find a specific item of information, is to divide the total information space into portions which can be displayed, and to provide hierarchical access to these "pages"; as one moves down the hierarchy then more detailed information is given about a smaller area of the information space. Another approach, which exploits specific structure in the data (in this case a tree structure), involves arranging or representing the data in a special way for presentation, as a Tree-Map (Johnson & Shneiderman, 1991; Shneiderman, 1992), or as a Cone Tree (Robertson, Mackinlay & Card, 1991).

While non-distortion-oriented techniques may be adequate for small text-based applications, their main weakness is that they generally do not provide adequate context for the user to support navigation of large scale information spaces. To overcome this shortcoming, distortion-oriented techniques have been developed and used, particularly in graphical applications. The main feature of these techniques is to allow the user to examine a local area in detail on a section of the screen, and at the same time, to present a global view of the space to provide an overall context to facilitate navigation (see Figure 3.1).

The growing interest in the application of distortion techniques in recent years (Leung, 1989; Hollands *et al*, 1989; Mackinlay, Robertson & Card, 1991; Misue & Sugiyama, 1991; Sarkar & Brown, 1992; Robertson & Mackinlay, 1993; Rao & Card, 1993) can be attributed to the availability of low cost and high performance graphics workstations. Farrand (1973) provided an early discussion of computer-based application of distortion-oriented display techniques. He considered the graphical fisheye and designed his DECR (Detail Enhancing, Continuity Retaining) lens to address what he termed the DETAIL x SCOPE problem in information display. In the context of a non-interactive presentation of cartographic maps, Kadmon & Shlomi (1978) described the Polyfocal Display. Kadmon & Shlomi laid down the mathematical foundation for a variety of distortion techniques and they also proposed the concept of a multi-focal projection.

The Bifocal Display (Spence & Apperley, 1982), which has been described in detail in the previous chapter, was an early computer-based distortion-oriented display technique. The original illustration of the Bifocal Display was a one-dimensional representation of a data-space whose area exceeded that of the screen (see Figure 3.1); the example used was an "in-tray" coupled with an application for an office environment. The Bifocal Display was later extended to a two-dimensional form for the presentation of topological networks (Leung, 1989) (see Figure 3.6). A variant of the Bifocal Display in one-dimensional form was later proposed by Mackinlay *et al* (1991) as the Perspective Wall.

Furnas's concept of a Fisheye View (Furnas, 1986) was based on textual trees, and an implementation of this technique was illustrated in the presentation of program code in one-dimensional form and a calendar in two-dimensional form. No mathematics for the graphical application of this concept were provided. A number of Fisheye View-like applications have been developed (Hollands *et al*, 1989; Mitta, 1990; Misue & Sugiyama, 1991; Sarkar & Brown, 1992; Schaffer, Zuo, Bartrun, Dill, Dubs, Greenberg & Roseman, 1992) which differ not only in their application domains, but also in their form.

The fast growing number of distortion-oriented techniques proposed by user interface designers calls for a taxonomy and a conceptual model to relate and delineate these techniques for two main reasons. First, a taxonomy will help to clarify the confusion of terminologies and unravel the mystique of ever increasing new presentation techniques confronting graphical user interface designers. Second, a well defined classification will help to make the comparison and generalisation of empirical results of experiments using these techniques a much easier task.

The main aims of this chapter are fourfold: (i) section 4.2 reviews distortion-oriented presentation techniques reported in current literature and explains their fundamental concepts, (ii) section 4.3 presents a taxonomy of these techniques clearly showing their underlying relationships, (iii) a conceptual model of distortion-oriented techniques is presented to show their roots and origins (section 4.4), and (iv) finally, section 4.5 discusses issues relating to the implementation and performance of these techniques.

4.2 A Review of Distortion-oriented Presentation Techniques

The application of distortion-oriented techniques to computer-based graphical data presentation has a relatively short history, although the concept of distortion or deformation has been used over many centuries by cartographers in various map projections. Modern distorted displays can be found in familiar representations as the London Underground map and many subsequent subway systems and topological networks.

The essence of these techniques is the concurrent presentation of local detail together with global context at reduced magnification, in a format which allows dynamic interactive positioning of the local detail without severely compromising spatial relationships. Figure 3.1 shows the application of a simple distortion technique (the Bifocal Display) in one dimension on a strip of graphical information. An illustration of the same approach in two dimensions is shown in Figure 3.5. With these types of techniques there is usually a focus region where detailed information is displayed; in its surrounding regions, a demagnified view of the peripheral areas is presented.

A distorted view is created by applying a mathematical function, which is called a transformation function, to an undistorted image. The transformation function for a presentation technique defines how the original image is mapped to a distorted view. A magnification function, which is the derivative of a transformation function, on the other hand provides a profile of the magnification (or demagnification) factors associated with

the entire area of the undistorted image under consideration. Figures 4.2a and 4.2b show the relationship of these two functions and illustrate how an elliptical object is transformed to its distorted form by applying the transformation function of a Bifocal Display in one dimension.

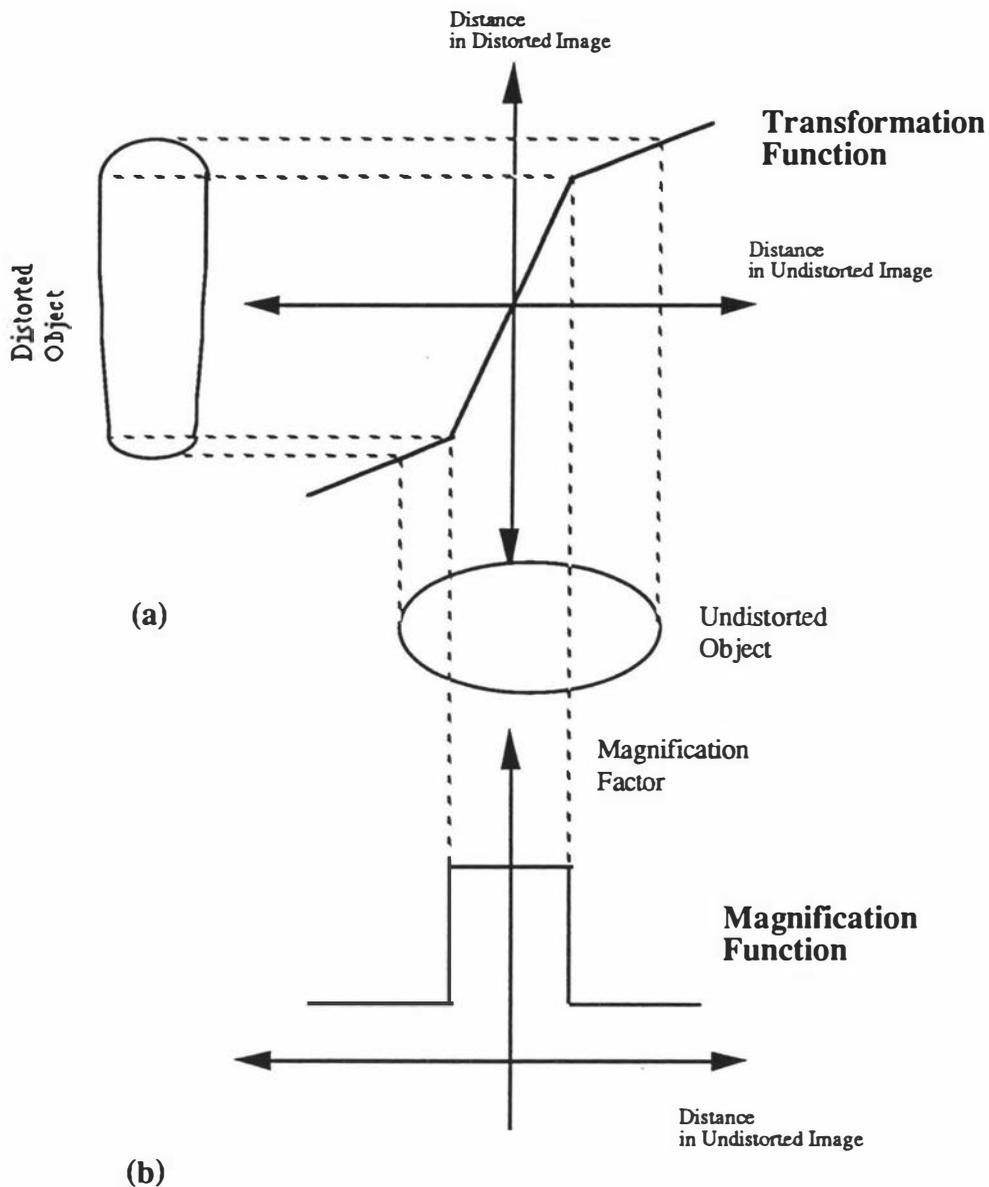


Figure 4.2 (a) The transformation of an elliptical object by applying the transformation function of a Bifocal Display in one dimension.
 (b) The corresponding magnification function of the Bifocal Display.

In a real time system, the user may initiate a shift of the focus region to view an adjacent area in detail using an interaction device. The system will then apply the transformation function to every entity contained in the re-positioned image and update the display with a corresponding shift in the focus region and its contents; the peripheral regions are also updated at the same time. The system response time depends on three factors: the complexity of the mathematical transformations involved, the amount of information and detail to be presented, and the computational power and suitability of the system used for implementation.

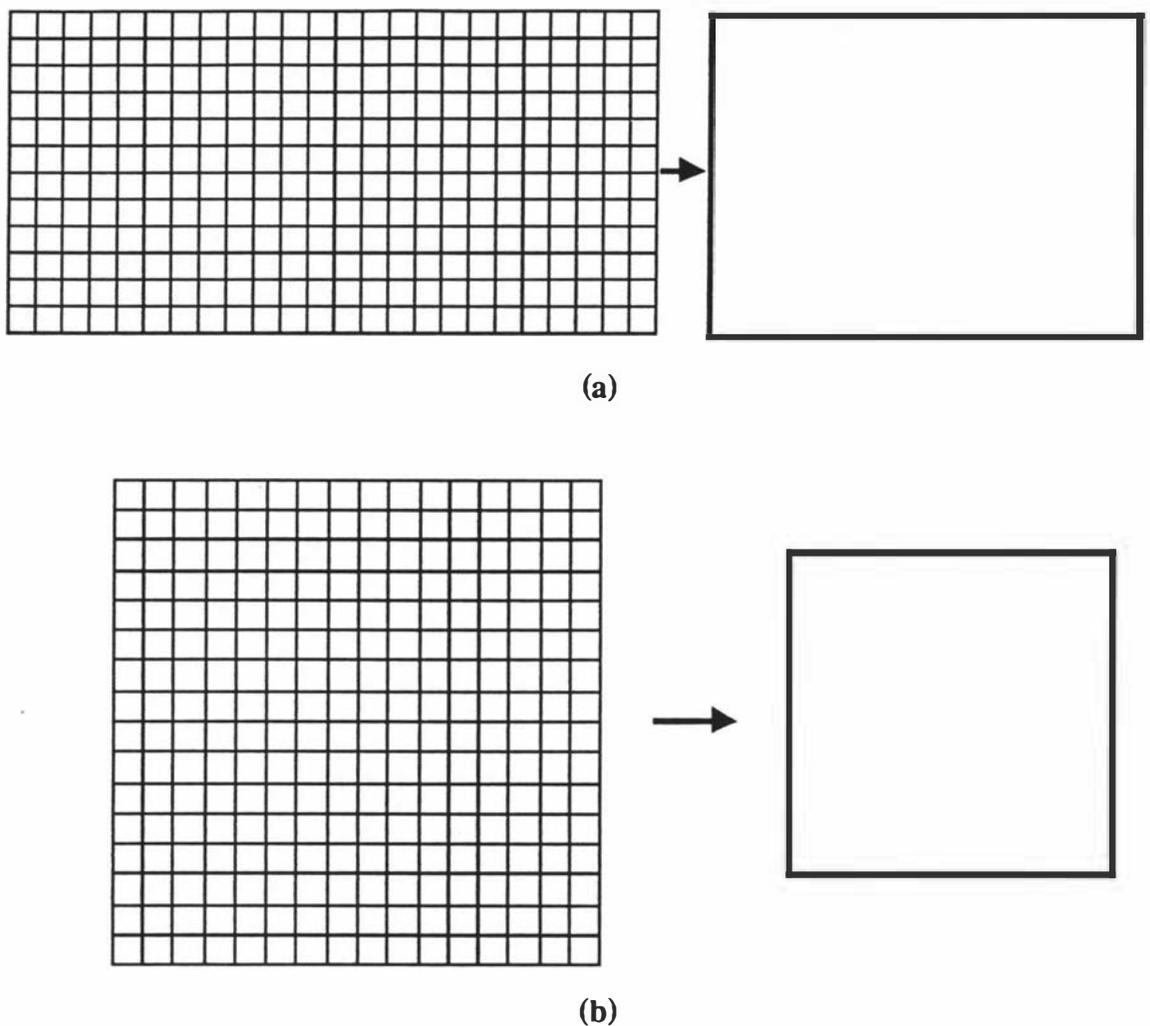


Figure 4.3 A rectangular grid is to be mapped onto a confined space by applying a distortion-oriented technique, (a) in one dimension, and (b) in two dimensions.

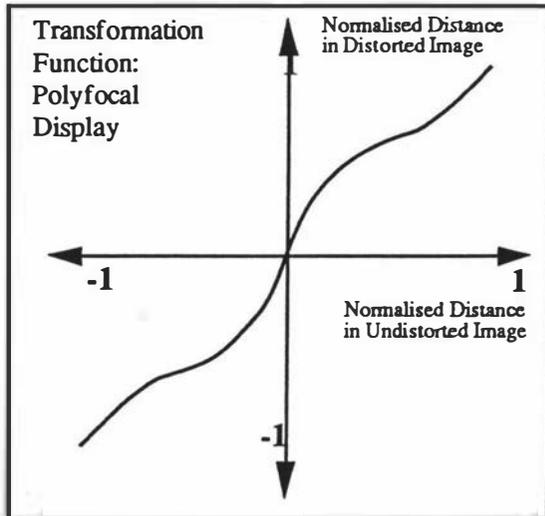
The following sub-sections present a historical review of distortion-oriented techniques and their underlying concepts in chronological order. The general form of their respective transformation and magnification functions are illustrated and applied, both in one and two dimensions, to grids of squares (Figures 4.3a and 4.3b) to provide a better appreciation of the differences and similarities between these techniques. In order to simplify the comparison of these techniques, the grids are "normalised" to the same sized display area before each distortion technique is applied. Further, system parameters are chosen so that similar magnification factors are applied in the central focus region.

4.2.1 Polyfocal Display (Kadmon & Shlomi)

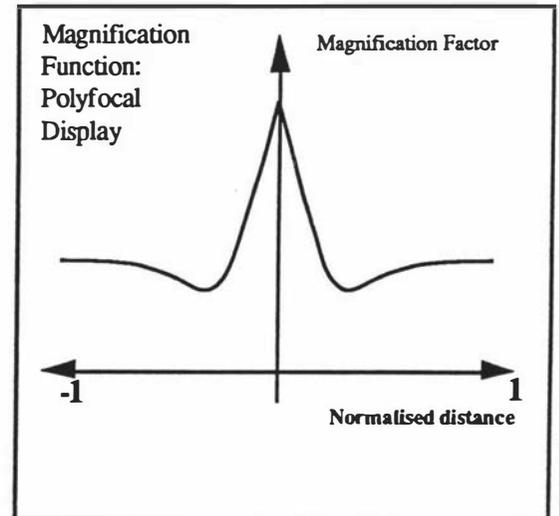
Kadmon & Shlomi (1978) proposed a polyfocal projection for the presentation of statistical data on cartographic maps. Although their concept was applied in a non-interactive situation, they made a valuable contribution in laying down a solid mathematical foundation for many later distortion-oriented presentation techniques, although many of the later developments have been carried out without the knowledge of this work. Kadmon & Shlomi also proposed an implementation of a multi-focal display. The graphical application of the Fisheye View (Sarkar & Brown, 1992) could well be considered as a special case of the polyfocal projection.

The fundamental concept behind the polyfocal projection in its one dimensional form can be illustrated by the transformation and magnification functions of Figures 4.4a and 4.5b, where the highest peak (Figure 4.4b) is the focus of the display. (For a rigorous mathematical treatment of the polyfocal display, readers should refer to Kadmon & Shlomi's (1978) paper). The curvature of the magnification function is controlled by two sets of parameters; one controls the magnification at the point of focus and the other the rate of change of magnification with distance from the point of focus. In cartographic terminology they are referred to as thematic variables. Figures 4.4c and 4.5d show the effects of this technique in one and two dimensions respectively. It should be noted that polyfocal projections distort the shape of the boundaries of the display. Further, the troughs in the magnification function, which are inherent in polyfocal projections, serve to compensate for the high magnification factors in the area surrounding the point of the focus.

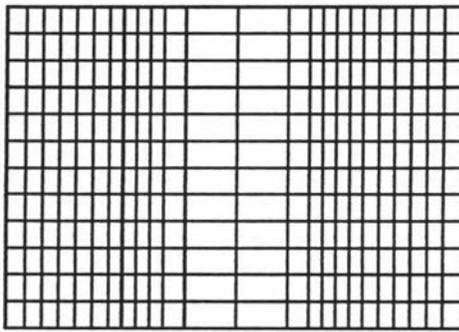
In the case of a multi-focal polyfocal projection, there will be multiple peaks in the magnification function, each contributing a certain amount of "pull" to the entire image. In theory there is no restriction on the number of these "peaks" in the magnification function; the only limitation is the computation time involved and the comprehensibility of the resulting distorted image.



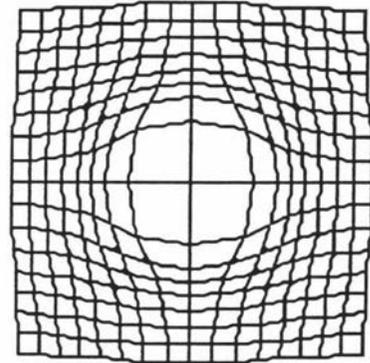
(a)



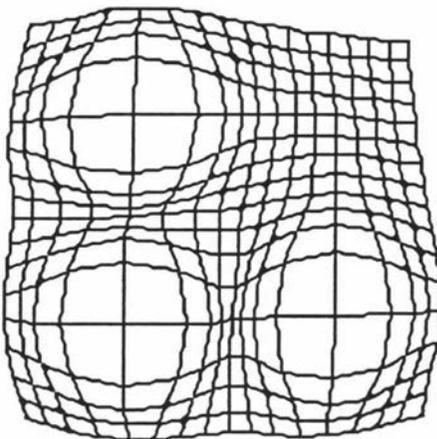
(b)



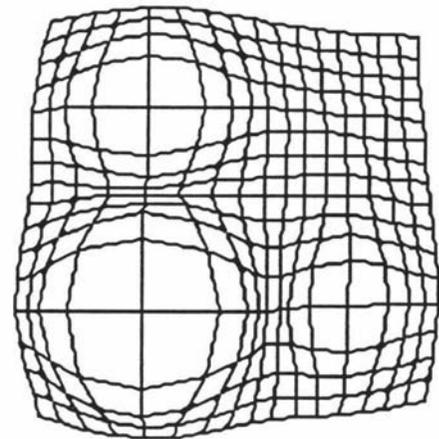
(c)



(d)



(e)



(f)

Figure 4.4 The Polyfocal Projection. (a) A typical transformation function of a Polyfocal Projection; (b) the corresponding magnification function; (c) the application of the projection in one dimension; (d) the application of the projection in two dimensions; (e) a multiple foci view of the projection using the same parameters for each focus point; (f) a multiple foci view using different parameters.

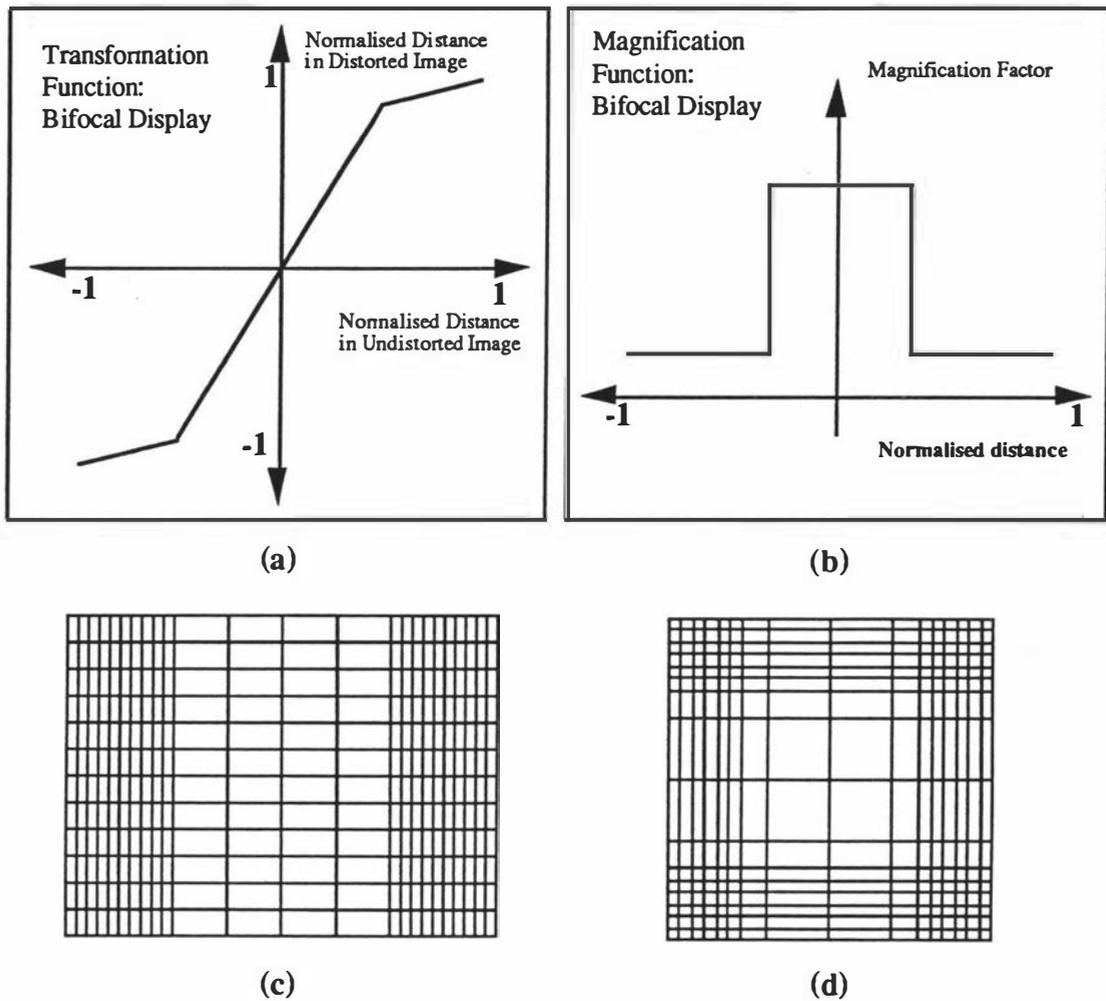


Figure 4.5 The Bifocal Display. (a) A typical transformation function; (b) the corresponding magnification function; (c) the application of the display in one dimension; (d) the application of the display in two dimensions.

Figures 4.4e and 4.4f show two displays with multiple foci; the former with the same parameters applied to each focus and the latter with different sets of values for each focus. It should be noted that it is possible to have zero magnification where a section of the display is effectively shrunk to nothing, thus creating a "vanishing area". Negative magnification factors may also be possible, creating overlapping views.

4.2.2 Bifocal Display (Spence & Apperley)

The Bifocal Display (Spence & Apperley, 1982) in a one-dimensional form involves a combination of a detailed view and two distorted sideviews, where items on

either side of the detailed view are compressed uniformly in the horizontal direction. Spence & Apperley used the mechanical analogy already referred to in Figure 3.1 to describe the display. The transformation and magnification functions for this technique are shown in Figure 4.5a and 4.5b. Figure 4.5c shows a one-dimensional Bifocal Display applied to a square grid. Although the Bifocal Display is relatively simple in terms of implementation and it does provide spatial continuity between regions, it has the disadvantage of discontinuity of magnification at the boundary between the detailed view and the distorted view. An analysis of the implementation requirements of the Bifocal Display based on special purpose memory management hardware has also been described (Apperley *et al*, 1982).

As mentioned in the previous chapter, Leung (1989) extended the bifocal concept to a two-dimensional form in an implementation of the London Underground map. Figure 4.5d shows the effects of this technique in two dimensions. The visual area is subdivided into nine regions with a central focus region (see Figure 3.5), and other eight regions which are demagnified according to the physical position with respect to the central focus region; the same demagnification factor is used in both x and y directions in these regions. It should be noted that because the four corner regions are demagnified in both x and y directions using the same scale, these areas are not distorted, they are just reduced in size.

4.2.3 Fisheye View (Furnas)

The Fisheye View concept was originally proposed by Furnas (1986) as a presentation strategy for information having a hierarchical structure. The essence of this technique is *thresholding*. Each information element in a hierarchical structure is assigned a number based on its relevance (*a priori importance* or API) and a second number based on the distance between the information element under consideration and the point of focus in the structure. A threshold value is then selected and compared with a function of these two numbers to determine what information is to be presented or suppressed. Consequently, the more relevant information will be presented in great detail, and the less relevant information presented as an abstraction, based on a threshold value. Furnas's Fisheye View was illustrated by two text-based applications, one involving a large section of program code and the other a calendar. Koike (in press) considers the potential problem of this technique for presenting trees with different number of branches and offers an interesting refinement using fractal algorithms.

Mathematically the *degree of interest (DOI)* function, which determines for each point in the hierarchical information structure how interested the user is in seeing that point with respect to the current point of focus, is given by,

$$DOI_{fisheye}(a|b) = API(a) - D(a,b)$$

where,

$DOI_{fisheye}(a|b)$ is the degree of interest in a , given that the current point of focus is b .

$API(a)$ is a static global value called *a priori importance* at point a ; API values are pre-assigned to each point in the structure under consideration, and

$D(a,b)$ is the distance between point a and the point of focus b .

It is apparent that the DOI function of the Fisheye View is an information suppression function. The illustrations which Furnas used were text based examples, and rather than involving demagnification *per se*, they involved the selective suppression and highlighting of components of the text depending on the prior Degree of Interest (DOI) values with respect to the object at the focus and a threshold value. The analogy with a traditional fisheye lens is cryptic. Information suppression, however, may be considered as orthogonal to spatial transformation. Furnas's technique, in the context of spatial transformation pertaining to distortion-oriented presentation techniques, can best be described by a magnification function as shown in Figure 4.6.

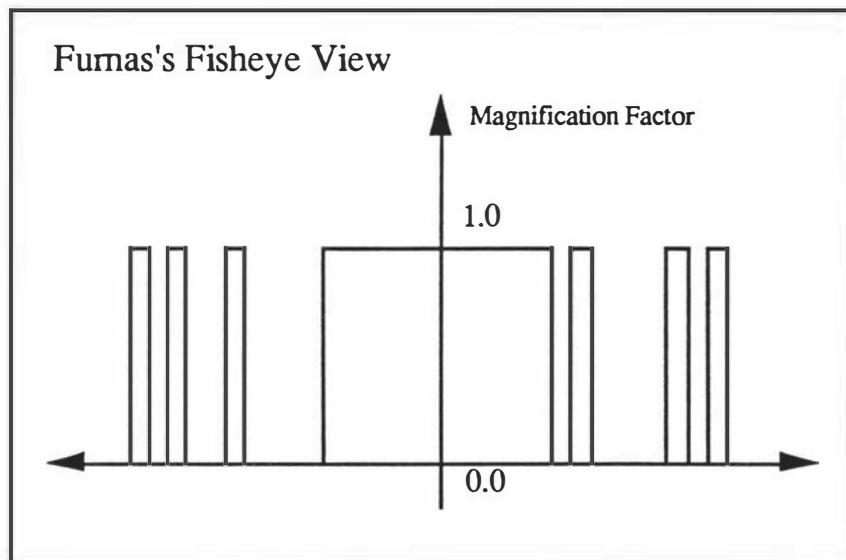


Figure 4.6 A typical magnification function for Furnas's "Fisheye View"

A number of other implementations, all claiming to use this technique, have been reported and have created some confusion as to what a "fisheye view" really means. These implementations are not only different in their application domains, but also in their form, and they will be examined in detail in later sections.

4.2.4 Fisheye View (Hollands *et al*)

Hollands *et al* (1989) represented a fictitious subway network using both a Fisheye View and a simple scrolling view, and compared the users' performance with these two interfaces. Users performed three different tasks: a route task, a locate/route task and an itinerary task. Although no details were provided of the implementation of the Fisheye View, the figures in the paper suggest it is a graphical implementation of a much more general fisheye concept, which has more in common with the Bifocal Display than with Furnas's DOI functions. Furthermore, the station symbols displayed in the focus region of the Fisheye View were smaller than those in the scrolling view, apparently contradicting the fundamental concept of *degree of interest (DOI)* (Furnas, 1986). The transformation and magnification functions used would appear to be similar to those of the Bifocal Display (Figures 4.5a and 4.5b).

4.2.5 Fisheye View (Mitta)

Mitta (1990) proposed a "fisheye" strategy for the presentation of aircraft maintenance data. The example used showed a solenoid assembly consisting of a number of components presented in different views. In each of these Fisheye Views certain components were suppressed so that users could focus their attention on the parts which were presented on the display screen. In the conclusion of the paper, Mitta wrote "*Thus, future research efforts are to examine how information should be selected, in addition to what information should be presented*" confirming that the technique used was an information suppression technique rather than the more conventional notion of a Fisheye View used by Hollands *et al* (1989).

Mitta made reference to Furnas's work on Fisheye Views and extended a multiple focus point version of the same technique.

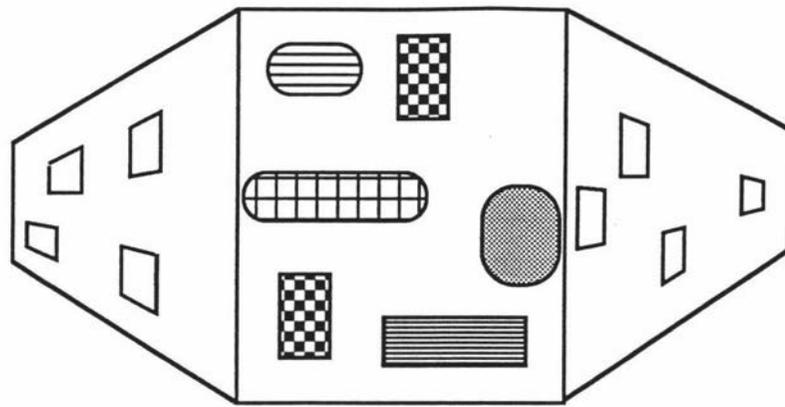
4.2.6 Perspective Wall (Mackinlay *et al*)

The Perspective Wall (Mackinlay *et al* 1991), a conceptual descendent of the Bifocal Display, is based on the notion of smoothly integrating detailed and contextual views to assist in the visualisation of linear information.

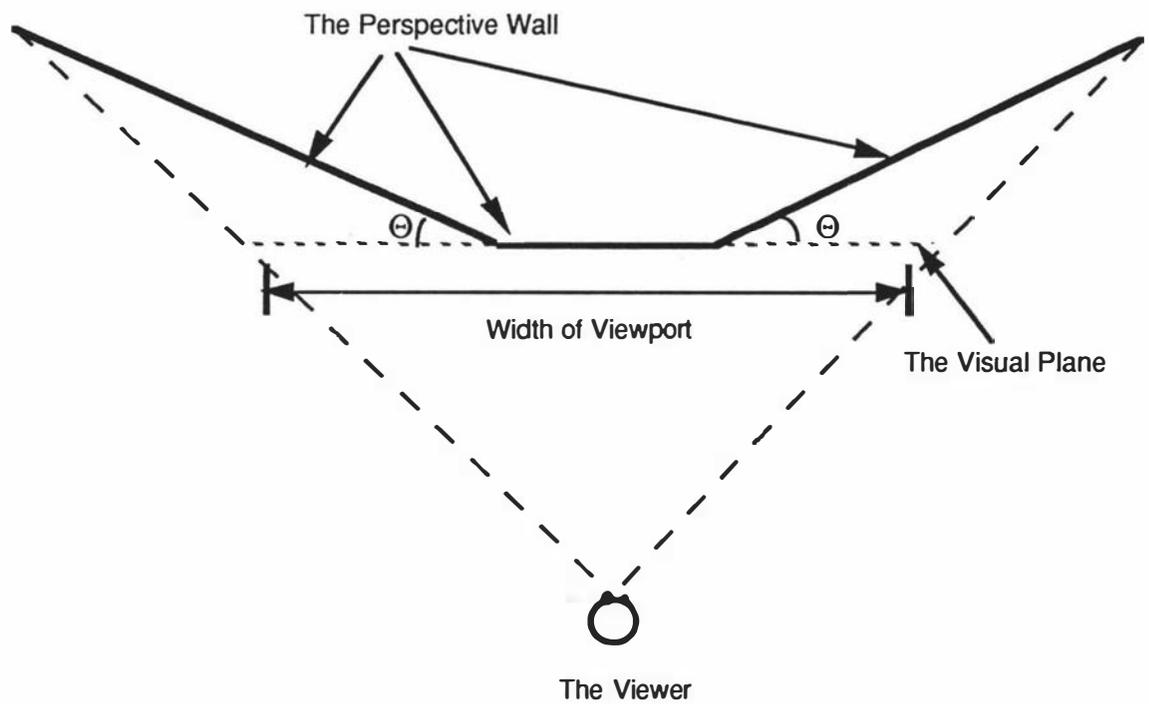
The principle behind the Perspective Wall is illustrated in Figures 4.7a and 4.7b. The two side panels, which show a distorted view of the out of focus regions, are demagnified directly proportional to their distance from the viewer; the corresponding transformation and magnification functions for this technique are shown in Figures 4.8a and 4.8b. Although this technique is inherently two-dimensional, for illustrative purposes its application to the two square grids in both one and two dimensions is shown in Figures 4.8c and 4.8d. The main distinction between this technique and the Bifocal Display is that in the out of focus regions, the Perspective Wall demagnifies at an increasing rate in comparison with the Bifocal's constant demagnification (compare the magnification functions in Figures 4.5b and 4.8b). This rate of increase in the magnification function of the two side panels depends on the angle Θ ; the greater this angle, the flatter the slope. There is a discontinuity in the magnification function at the points where the two side panels meet the middle panel; the bigger the angle Θ , the greater the discontinuity.

The view generated by the Perspective Wall is dependent on a number of parameters: the length of the wall, the width of the viewport, the angle Θ , the size of the central region, etc. To get a better understanding of the Perspective Wall, consider the effect of increasing the angle Θ (Figure 4.7) while all other system parameters remain constant. As the angle Θ increases with the two side panels tilting backwards (see Figure 4.7b), the viewer will, as a consequence, have to be positioned further away from the wall because the width of the viewport is fixed. It should be noted that the position of the viewer determines the projection of the two side panels on the visual plane (see mathematical derivation of the transformation function in Appendix B). As the angle Θ is increased further, there is a position where the viewer is essentially positioned at infinity. At this point the demagnification in the peripheral regions will be constant, and it can be seen that the Bifocal Display is actually a special case of the Perspective Wall. This point can also be seen with the mechanical analogy of Figure 3.1; a close-up view would produce a Perspective Wall, and a view from infinity, a Bifocal Display.

The Perspective Wall does add a full 3D feel to the otherwise flat form of the Bifocal Display. However, this effect is produced at the cost of wasting expensive "real estate" in the corner areas of the screen, contrary to one of the prime objectives of distortion techniques to maximise the utilisation of the available display area. This particular shortcoming of the Perspective Wall has been more recently overcome with the development of the Document Lens technique (Robertson & Mackinlay, 1993).



(a)



(b)

Figure 4.7 (a) With two side panels positioned at an angle the Perspective Wall provides a distorted view to the viewer.

(b) A plan view of the Perspective Wall showing the relationships between the wall, the viewport, and the viewer.

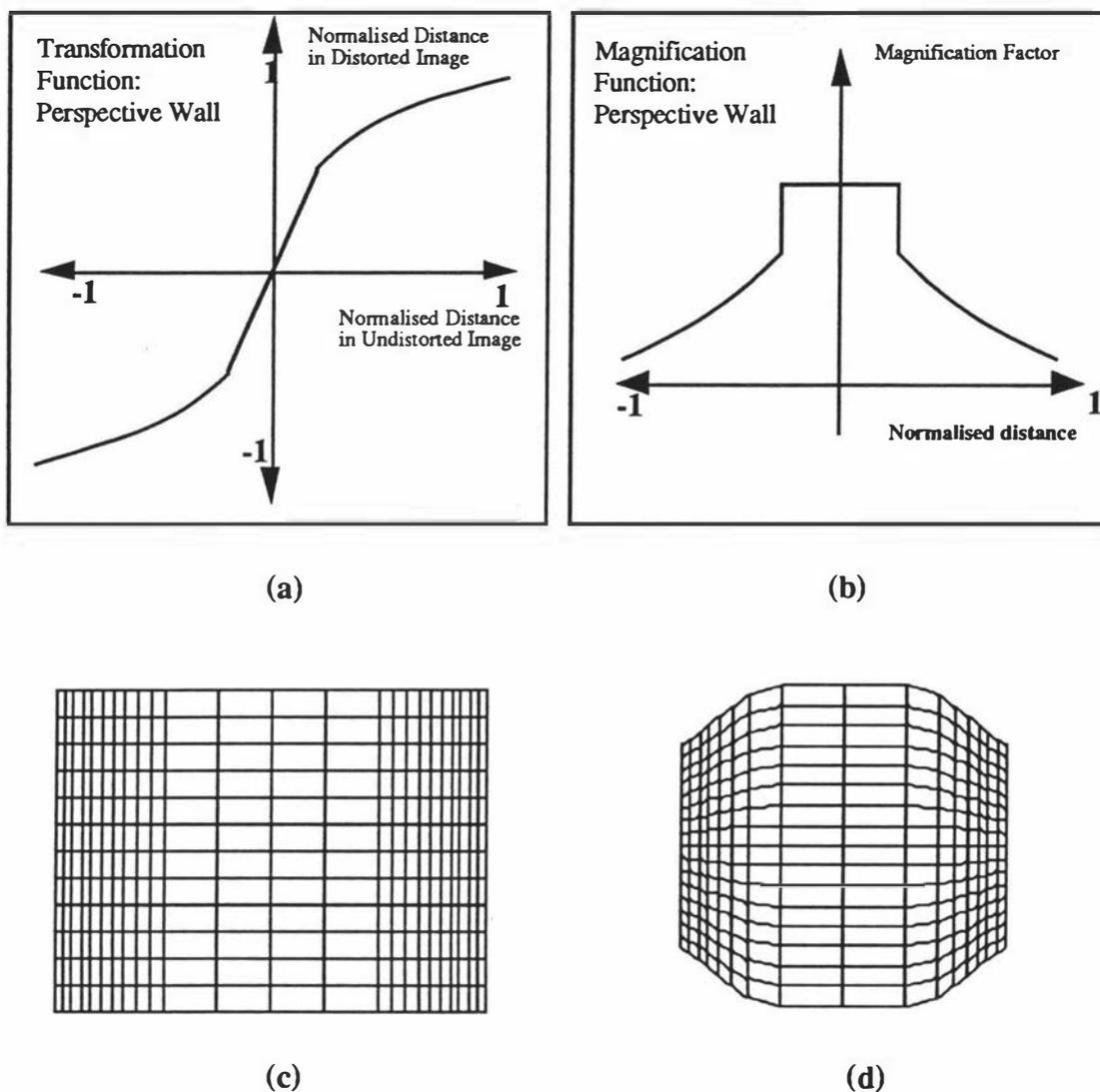


Figure 4.8 The Perspective Wall. (a) A typical transformation function; (b) the corresponding magnification function; (c) the application of the wall in one dimension; (d) the application of the wall in two dimensions. Here the number of dimensions relates to the dimensions in which the perspective transformation is applied on the projection, not to the dimensionality of the model on which the projection is based.

4.2.7 Graphical Fisheye Views (Sarkar & Brown)

Sarkar & Brown (1992) extended the Furnas's fisheye concept and laid down the mathematical formalism for graphical applications of this technique. They proposed two implementations, both of topological networks, one based on a Cartesian coordinate transformation system and the other on a polar system. Owing to the nature of polar transformation, in theory a straight line and rectangle will normally be transformed into a

curved line and a curvilinear rectangle respectively. To overcome this problem, the transformation was applied only to the nodes of the structure, and the nodes were then connected by straight lines. The transformation and magnification functions for the Fisheye View are respectively, (see Figures 4.9a and 4.9b)

$$T(x) = \frac{(d+1)x}{(dx+1)} \quad \text{and} \quad M(x) = \frac{(d+1)}{(dx+1)^2}$$

where,

d is called the distortion factor, the larger this number is, the bigger the magnification and the amplitude of the peak in the magnification function, and, x is the normalised distance from a point under consideration to the point of focus. x can have a value $0 \leq x \leq 1$. If $x = 0$, the point under consideration is at the point of focus and if $x = 1$, it is at a position furthest away from the point of focus on the boundary.

Figure 4.9c shows the application of this Fisheye View in one dimension. Figure 4.9d shows the two-dimensional Fisheye View with a Cartesian coordinate system, and Figure 4.9e with the transformation based on a polar coordinate system. It is interesting to note that the polar Fisheye View produces a rounded appearance which unfortunately does not provide a natural look when implemented on a rectangular screen. Sarkar & Brown further proposed that the rounded appearance of the Polar Fisheye View be re-mapped onto a rectangular space; the result of this modified transformation is illustrated in Figure 4.9f. Surprisingly, the appearance of Figure 4.9f bears some resemblance to that of a Perspective Wall (Figure 4.8d). As this perspective transformation is applied fully in two dimensions (the perspective transformation is not applied in the vertical direction in the middle panel for the Perspective Wall proposed by Mackinlay *et al*), a more appropriate name for this technique would be Perspective Space (Leung & Apperley, 1993a).

While these fisheye transformations provided the spatial distortion in two dimensions, Sarkar & Brown introduced a further information magnification in the third dimension based on the concept of *a priori importance* (*API*) proposed by Furnas. Their implementation of *API* was extended to three separate functions called $Size_{fisheye}$ (*S*), Visual Worth (*VW*) and $Details_{fisheye}$ (*DTL*). The purpose of these functions is twofold: first, they provide a flexible information suppression/enhancement mechanism to generate an effective Fisheye View, and second, the resulting display provides the viewer with a three-dimensional feel. This technique is potentially very powerful in displaying information which is multi-layered and globally organised in a hierarchical tree or network structure.

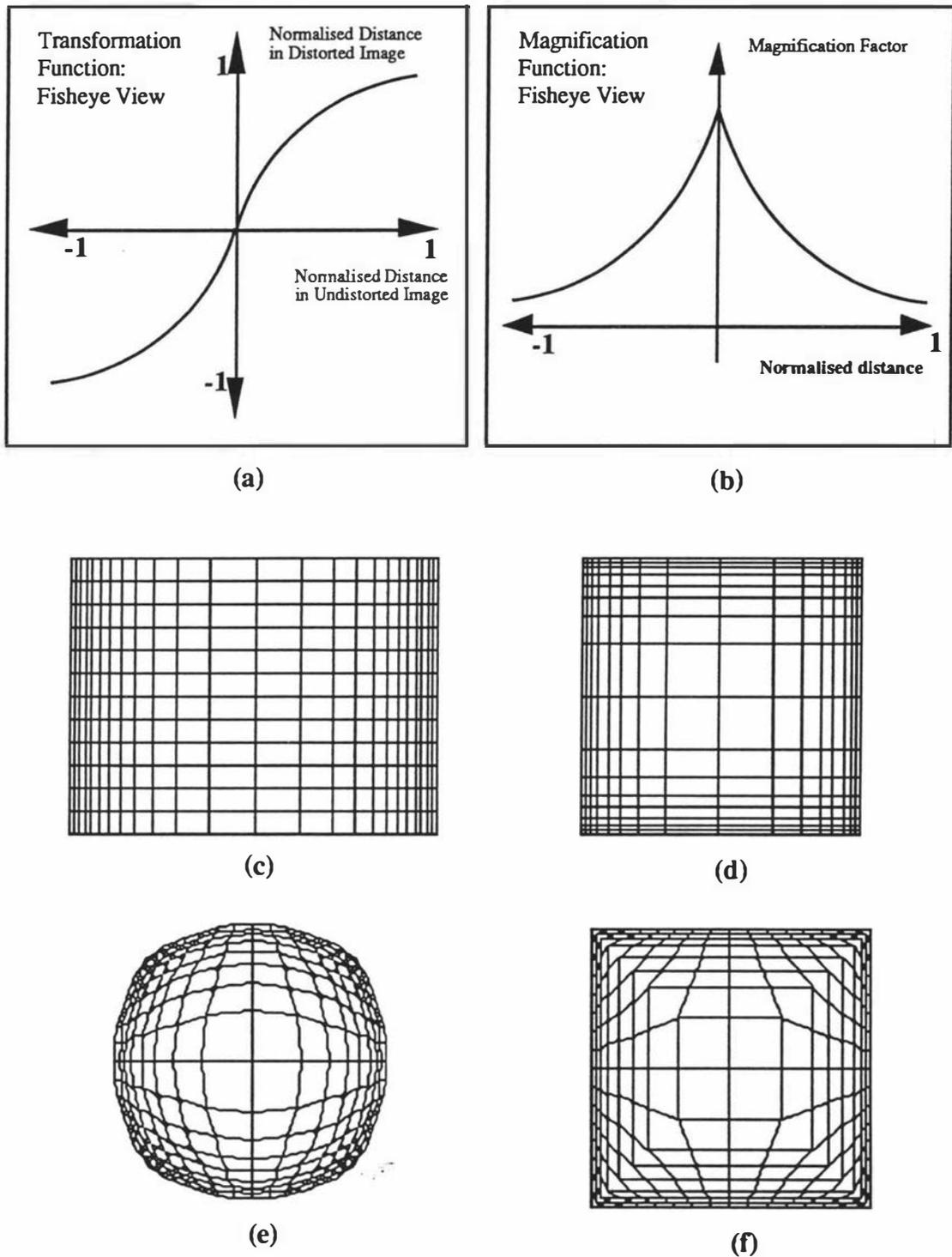


Figure 4.9 The Fisheye View. (a) A typical transformation function; (b) the corresponding magnification function; (c) the application of the Fisheye View in one dimension; (d) a Cartesian Fisheye View in two dimensions; (e) a polar Fisheye View; (f) a normalised polar Fisheye View.

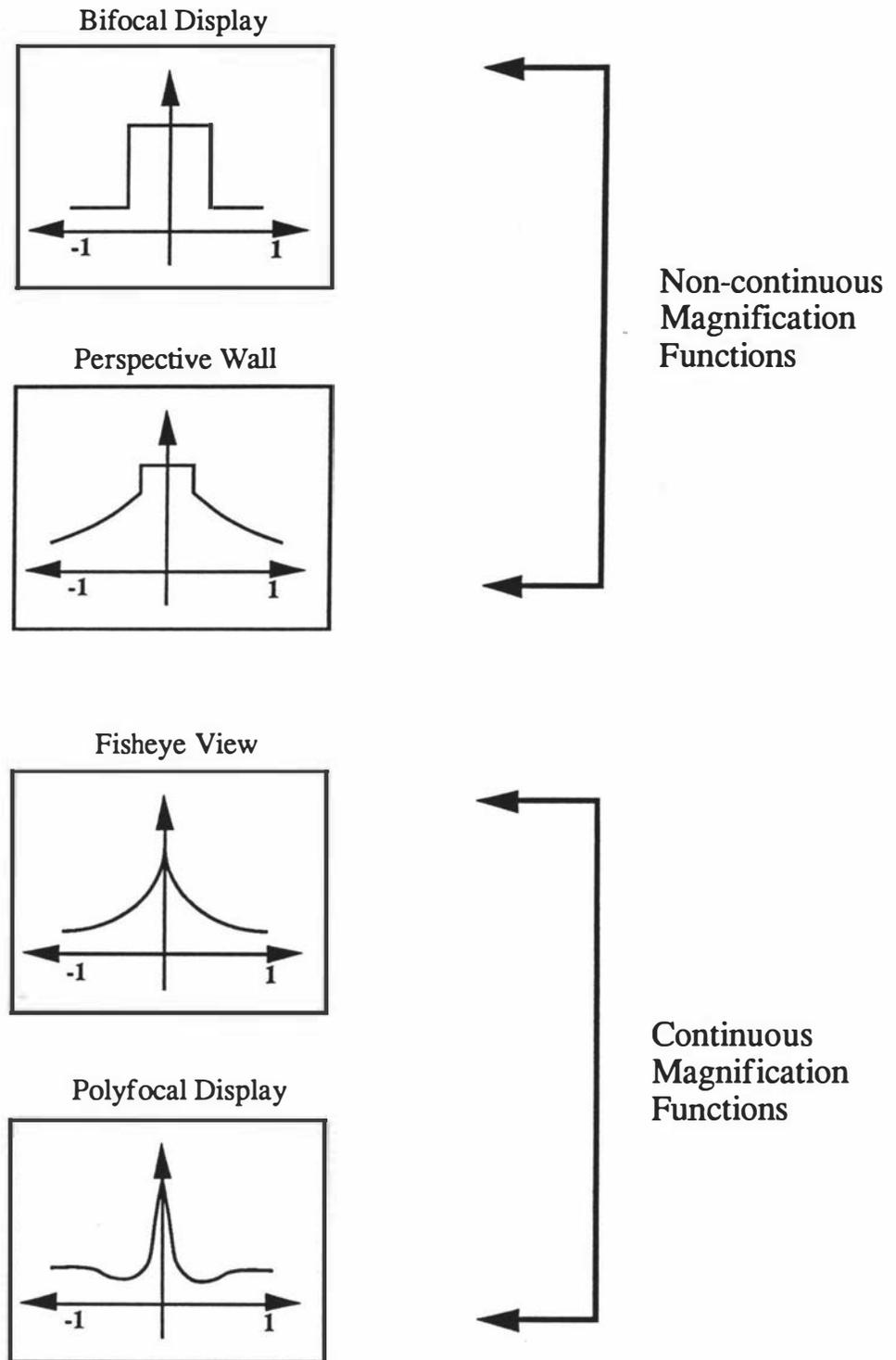


Figure 4.10 A taxonomy of distortion-oriented presentation techniques.

Misue & Sugiyama (1991) described two transformation functions (polar and Cartesian versions) for graphical Fisheye Views which have some similar properties to those of Sarkar & Brown.

4.3 A Taxonomy of Distortion-oriented Presentation Techniques

An examination of the transformation and magnification functions of the distortion-oriented presentation techniques described in the previous section (see Figure 4.10) reveals their underlying differences and similarities. These techniques can be conveniently classified in terms of their magnification functions; basically, there are two distinct classes. One class of these techniques has piece-wise continuous magnification functions; the Bifocal Display and the Perspective Wall are typical examples. The other class has continuous magnification functions; the Fisheye View and the Polyfocal Projection belong to this second class.

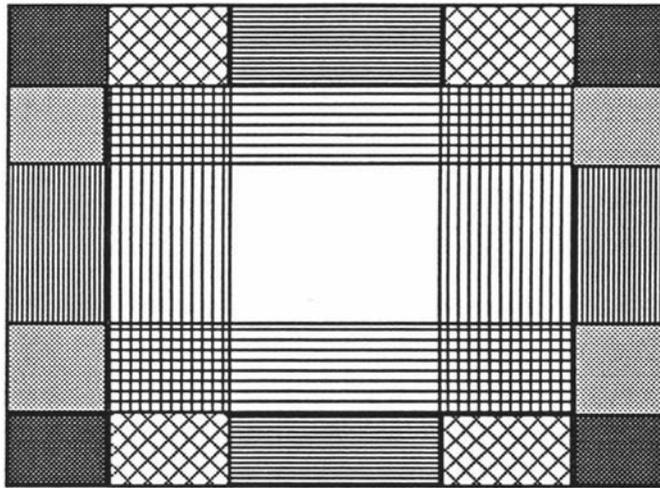


Figure 4.11 The 25 regions that would be generated by extending a two-dimensional Bifocal Display to incorporate three distinct magnification levels, rather than two.

Techniques with piece-wise continuous functions can be further classified into those with constant or varying magnification functions; the Bifocal Display belongs to the former sub-class and the Perspective Wall the latter. As explained in Section 4.2.6, the Bifocal Display is a special case of the Perspective Wall. A display which has multiple discrete levels of magnification in the magnification function could be generated; the limitation of extending the Bifocal Display concept to a higher level is imposed only by the system's resources. Further, the magnification factors used in these levels may be chosen in such a way that the function approximates to a continuous one. Figure 4.11 shows the general layout of a display with three magnification levels, and Figure

4.12 shows the magnification function for a display with 4 magnification levels which approximates that of a Fisheye View. Applications, and the complexity involved in the implementation, of these techniques are discussed in later sections.

Techniques with continuous magnification functions have one undesirable attribute; they tend to distort the boundaries of the transformed image. The bigger the magnification factor at the focus is, the bigger this distortion at the boundaries will be. This is because these techniques are generally applied radially rather than independently in the x and y directions. Consequently, the corner areas are pulled in towards the point of focus. This problem can be overcome in two ways as implemented by Sarkar & Brown (1992) in their Cartesian and Polar Fisheye Views. First, the transformation may be applied independently in the x and y directions as in the Cartesian Fisheye View (Figure 4.9d). Second, the distorted boundaries can be remapped onto a rectangular size of the display area as illustrated in Sarkar & Brown's Polar Fisheye View (Figure 4.9e). It should be noted that because of the irregular shape of the boundaries in the Polyfocal Projection, which is inherent in its transformation, more extensive calculation would be required in this case to perform the re-mapping operation.

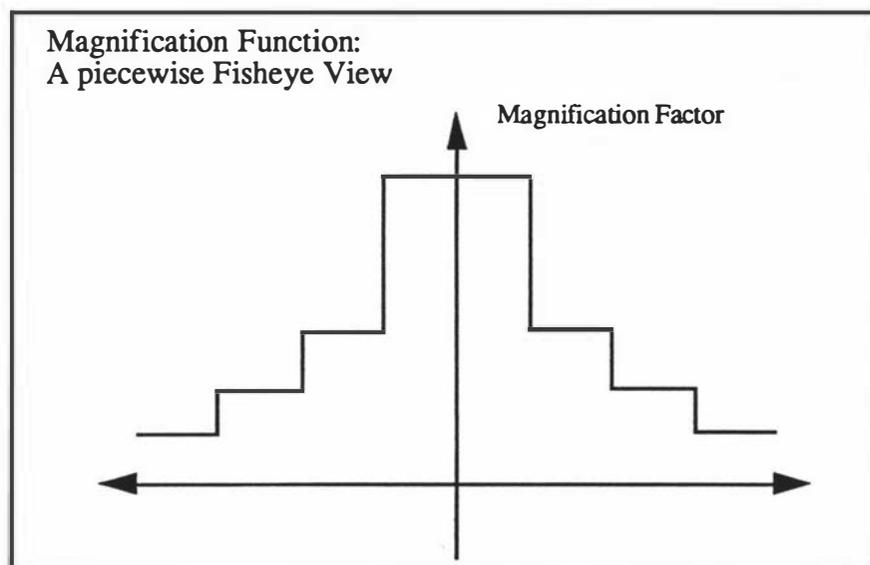


Figure 4.12 The magnification function of a piecewise Fisheye View.

A closer examination of the magnification functions for the Fisheye View and Polyfocal Projection (Figure 4.10) shows their strong similarities in their general profiles. One could consider the Fisheye View as a special case of Polyfocal Projection.

The difference in these two functions is the dips in Polyfocal Projection's magnification function. It is the dips in the Polyfocal Projection's magnification function which make it possible for this technique to support a two-dimensional multiple focus presentation as shown in Figure 4.4e and 4.4f; techniques which do not have this property in their magnification function will not be able to provide a flexible two-dimensional multiple focus system. This point is further discussed in a later Section 5.2 on implementation issues.

4.4 A Conceptual Model

While the taxonomy in the previous section gives a global view of distortion-oriented techniques, a conceptual model is proposed here to provide a better insight and understanding of their underlying concept.

The simplest way of visualising the working of a distortion-oriented presentation technique is to treat the displayed information as if it was printed on a stretchable rubber sheet mounted on a rigid frame*. This is an effective analogy which has been used by various researchers to describe distorted displays (Tobler, 1973; Mackinlay *et al*, 1991; Sarkar, Snibbe & Reiss, 1993). The rubber sheet is densely populated with information to the extent that in its unstretched form, the viewer can see only the global context of the information structure and is not able to make out any detailed information from it. In order that a viewer can examine a particular section to access detailed information, the rubber sheet has to be stretched. Any stretching of the rubber sheet is analogous to applying magnification to a section of the screen. As the rubber sheet is mounted on a rigid frame, any stretching in one part of the sheet results in an equivalent amount of "shrinkage" in other areas. The consequence of this stretching and shrinking of the sheet is an overall distorted view. The amount of stretching or magnification and the manner in which it is applied on the sheet depends entirely on the magnification function of the distortion technique used.

To illustrate how this conceptual model works, consider that the Bifocal Display technique is to be applied on a rubber sheet mounted on a rigid frame as shown in Figure 4.13a. Three points, **a**, **b** and **c** are marked on the sheet to show the effect of stretching. The dotted lines enclose an area in the middle to be magnified in order that the viewer can examine its contents in detail; forces are applied along these lines to provide the magnification effect.

* It will be necessary for the edges of the sheet to be able to slide along the edges of the frame.

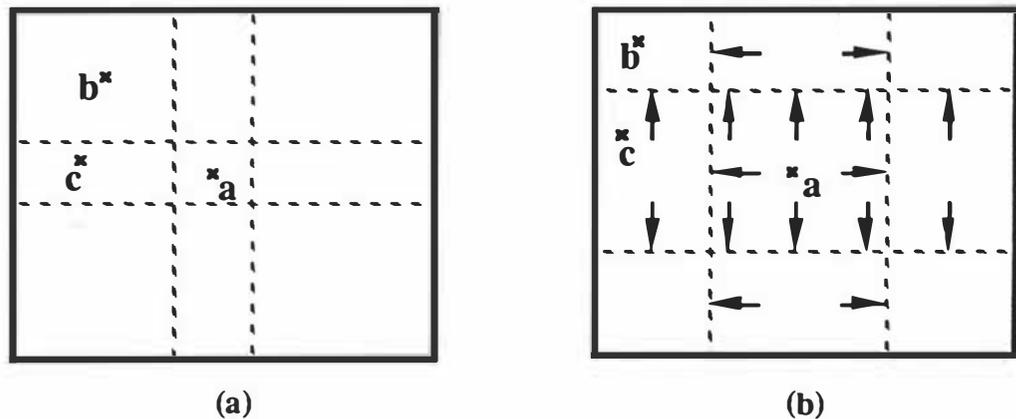


Figure 4.13 (a) An unstretched rubber sheet mounted on a rigid frame and the positions on it of 3 points a , b and c . Stretching is to be applied at the dotted lines.

(b) The arrows indicate the directions of stretching applied to the sheet. Point a is not displaced as it is at the focus. Points b and c are both displaced.

Figure 4.13b shows the sheet after stretching is applied in the directions of the arrows. As point a is located exactly at the point of focus and all the forces balance out, no displacement results at point a . Point b experiences two orthogonal forces as a consequence of the stretching applied near the top left hand corner area. The stretching in these two directions causes b to be displaced in both directions towards the top left hand corner. As a result, the four corner areas are being shrunk by an equivalent amount to accommodate the excess area caused by the stretching. Point c experiences three forces, two stretching forces applied vertically and a compressing force horizontally. If point c were situated at the mid-point between the two dotted lines, no vertical displacement would take place; in this case because c is situated above this mid-point, the resultant force displaces point c upwards. At the same time, the compressing force point c experiences causes shrinkage in the horizontal direction as indicated in Figure 4.13b.

In the case of a multiple focus view, the situation is similar. The only difference is that stretching or magnification will occur in a greater number of areas on the rubber sheet. The important fact is that the sum of all stretchings or magnifications must be equivalent to the total shrinkages or demagnifications. Otherwise, the rigid frame holding the rubber sheet would deform either because of insufficient surface to accommodate the

"overstretched" sheet or because of an oversupply of space to fit an "overshrunk" sheet. The former situation applies to the Polyfocal Projection (Figures 4.4d, 4.4e and 4.4f) while the Polar Fisheye View (Figure 4.9e) and the Perspective Wall (Figure 4.8d) are examples of the latter. As explained in the previous section, techniques with continuous magnification functions by their mathematical nature deform the rectangular frame because of the radial influence inherent in the transformation. "The unity gain at the periphery insures continuity retention in the interface to the real world" (Farrand 1973, p.32).

4.5 Discussion

4.5.1 Performance Issues

Although the techniques under consideration may be used to display static distorted images on the computer screen, in the context of human-computer interaction an input device will be used to support real time interaction by users. To allow presentation and navigation of an information space, there are generally three basic interaction methods to effect a change of viewport using an input device: scrolling, pointing and selecting, and dragging.

With scrolling, as the user initiates a movement with the input device (e.g. moving a finger on a touch sensitive screen or scrolling a mouse), the system detects the direction of the movement and updates the image on the display screen in real time; the amount of movement effected on the central focus area is directly proportional to the scrolling action on the input device made by the user. Depending on system response time, the implementation of scrolling usually involves the creation and the display of a number of intermediate images between the source image to the target image to provide a smooth, continuous visual transition as the focus region is re-positioned. To improve performance, detail can be omitted from the non-focus areas during interaction (Robertson & Mackinlay 1993).

With pointing and selecting, the user moves the central focus region to another location by first positioning the cursor using an input device, and then activating it to select the desired point of interest. The new display with a change of the focus region and its surrounding areas, will then be presented.

Dragging incorporates features of both the previous methods. The user selects an item of interest and at the same time moves it (typically by a concurrent scrolling action) with an input device to a position desired by the user for detailed examination.

To maintain context with this form of interaction, it will usually be necessary to have the central focus region fixed with respect to the display surface, with the data space apparently moving underneath. This will necessarily result in some regions of the display not being fully utilised if the point of interest is near a corner of the space, and in some areas of the space either not being shown, or being severely distorted.

Distortion-oriented techniques are inherently complicated in their implementation and some require a significant amount of system time to generate a new image. While an excessively long system response time would render an interface "unusable", this problem may be overcome by using dedicated computer hardware and memory management systems to support the implementation of such techniques (Apperley *et al*, 1982; Card *et al*, 1991). Further, as general purpose graphics hardware becomes increasingly sophisticated and powerful, effective software solutions have become practicable (Robertson & Mackinlay, 1993). It should also be noted that a system response time that is too fast could be just as disconcerting to the user. The sudden shift of a distorted view or any fast scrolling movement on the display screen could cause visual discomfort to the viewer over prolonged, continuous use. This effect is similar to watching a home video which has been taken by an amateur who panned the view jerkily at high speed.

Although there has been an increasing amount of research carried out on user performance in reading moving text on computer displays (Kang & Muter, 1989; Chen & Chan, 1990), little work has been done to investigate the effects of moving graphical images or to find out the optimum speed for scrolling graphical images on computer screens. Before empirical findings in this research area are available, systems with too short a response time will have to be slowed down by introducing delays during image updates on a trial and error basis. Fortunately, this problem relates only to high performance computer systems and generally it is easier to slow a system down than to speed it up.

4.5.2 Implementation Issues

The selection of an interface and its implementation are often dictated by the system hardware available, and its computational power. The complexity of a presentation technique will, therefore, have much influence on this decision. Although distortion-oriented techniques tend to be complex in their implementation, their complexities differ quite widely and primarily depend on the mathematical transformation functions used. Furthermore, very often trade-offs between the computational power of the hardware and system memory can be made to yield optimum implementation. For example, distorted displays based on stepwise magnification functions may have their

different views created and stored in memory in advance. The generation of a distorted view in real time will involve only the cutting and pasting of various sections of these bit maps stored in memory. Generally, systems with less computational power perform the operation of shifting graphic bit maps much faster than that of carrying out complicated mathematical calculations in real time. However, such systems do require adequate on-board memory to support the interface for satisfactory performance. In the implementation of the London Underground map using the Bifocal Display technique described in the previous chapter, four separate bit maps, each with different magnifications applied in x and y directions, are stored in memory; altogether, the four bit maps take up six megabytes of system memory. As the user scrolls the mouse, the Bifocal Display is generated by cutting and pasting various sections of these bit maps in real time to generate the nine regions as shown in Figure 3.5. A similar technique has been applied in implementing the stepwise magnification function of the Document Lens, where the text is rendered for each of the five regions of a truncated pyramid in advance, and then clipped, scaled and translated as appropriate during interaction (Robertson & Mackinlay 1993).

Display techniques using a continuous magnification function pose a problem for this implementation method. This is because of the continuum of magnification factors the system will have to cater for at every possible position of the point of focus on the image; the number of bit maps that have to be stored will be too large to be practical for implementation. One way of overcoming this problem is to use a piecewise continuous magnification function to approximate a continuous function (see Figure 4.12). This method is an extension of the Bifocal Display to multiple magnification factors with a stepwise function*. It can be shown that if the number of distinct magnification levels is n , the number of bit maps the system will have to maintain is n^2 . For example, Figure 4.11 shows a two-dimensional Bifocal Display extended to have 3 distinct levels of magnification; there are 25 regions on the screen, and nine distinct mappings of the data to the display.

Interfaces with a scrolling-style interaction typically use this multiple bitmap method to generate the distorted view and therefore require less computational power but demand greater system memory. In contrast, interfaces with dragging and pointing and selecting inputs will rely on the computational power of the system to generate the images by performing the mathematical transformation in real time. Dedicated hardware to support the interface may be considered for implementation if a piecewise approximation of the transformation function is not desirable. It is interesting to note

* It would be tempting to refer to this as a trifocal, quadfocal, etc, display. However, because of the use of the term polyfocal display to refer to a display with multiple foci, rather than multiple magnification factors, this terminology has been avoided.

that although the Perspective Wall has a piecewise continuous magnification function, the mathematical transformation for the two side panels involves fairly complicated calculations. However, for applications where the displayed graphical data may be updated in real time, the bitmap-oriented implementation approach, which relies on pre-generated bitmaps, would be inappropriate.

Multiple focus views, which are akin to a multiple window environment in some text-based and graphical systems, are often desirable. For example, if the user wishes to examine two entities which are located at the extremes of the display, a multiple focus view would facilitate this application. However, there are some inherent conceptual limitations with the Cartesian (independent x and y) techniques in implementing multiple focus views. To illustrate this point, consider the case where two focus views A and B are to be created on a Bifocal Display as shown in Figure 4.14. Because of the inflexibility in the transformation function, two unintended focus views are created at x and y as a side effect. This inflexibility typically applies to techniques whose magnification functions do not have a dip in them like that of the Polyfocal Projection (Figure 4.5b). One way of alleviating this problem is to facilitate a pop-up window type arrangement to support multiple views. However, this may create additional navigational problems for the user because of the discontinuity of the presentation in the detailed and demagnified views on the display.

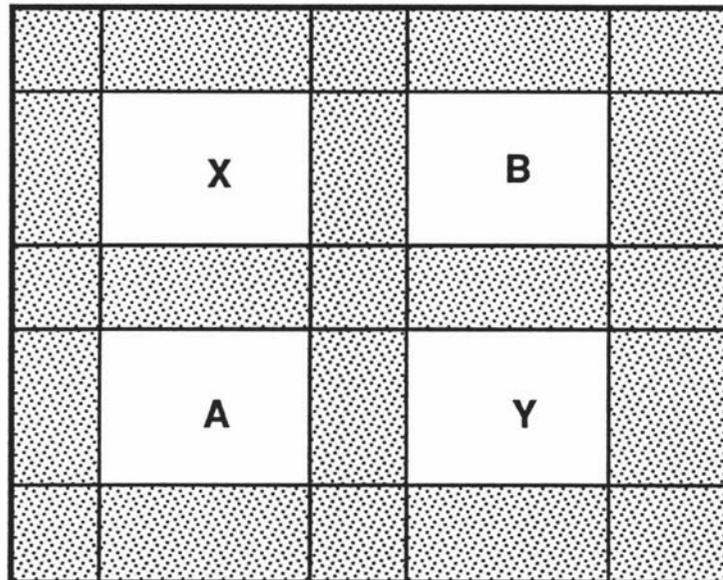


Figure 4.14 A common problem with multi-focus presentations. Intended focus areas are A and B . Unintentional focus areas X and Y are created.

map examining a small area in detail while maintaining global context of the map. When the user has located the station of interest, in this case Bond Street station, the embedded information is then revealed. This technique is potentially powerful and greater research effort should be focused on exploring the application domains for such hybrid approaches.

Distortion-oriented techniques are very useful in solving the spatial problem, however they should be used with some caution. Due consideration should be given to the type of information to be conveyed and how it will be perceived by the user. For example, in applications where the information to be presented is not well structured, these techniques may not have the desired effect. It should be pointed out that the Polyfocal Projection was originally intended for thematic cartography where maps are presented with a specific theme such as population density or temperature, rather than to show the absolute spatial distances between cities or countries. Leung & Apperley (1993*b*) discuss the relationship between these presentation techniques, the nature of the original data and its graphical representation, the physical characteristics of the display system (including resolution), the style of interaction, and the task being carried out.

4.6 Conclusion

There are generally two types of data in large computer-based information systems: those with a high information density and those with a spatial relationship. The Fisheye View concept that was first proposed by Furnas and later extended by Mitta, is an information suppression technique for the former. In this context, the suppression of information creates an "information distortion". Such techniques are very different to those applied to spatial problems.

This chapter has presented a taxonomy and a conceptual model of graphical distortion-oriented presentation techniques for spatial problems. Depending on the problem domain, these techniques may be applied in both one or two dimensions. Based on their magnification functions, distortion-oriented techniques may be classified into two categories: those with continuous functions and those with non-continuous functions. The Bifocal Display and the Perspective Wall belong to the former class, and the Polyfocal Projection and the Fisheye View to the latter. From an implementation viewpoint, multiple focus regions are practical only with the Polyfocal Projection because other distortion-oriented techniques create extra unintended focus regions as a side effect.

The formalism put forward by Sarkar & Brown on the Fisheye View has laid down the ground work for graphical application of this technique for spatial problems. However, a number of variations of the implementation of this technique are possible.

The conceptual model presented in section 4.4 has shown how magnification and demagnification work in tandem to create the desired distorted view. There is really no limitation on how these distorted views could be generated. A simple way of explaining these distortion techniques is to treat the display surface as a stretchable sheet of rubber mounted on a rigid rectangular frame. Magnification or "stretching" is carried out based on some mathematical transformation operating within that space. The basic law governing distortion-oriented techniques, which is a corollary of Newton's third law of motion, simply states that "where there is a magnification, there will be an equal amount of demagnification to compensate for the loss of display area in a confined space; otherwise the area of that confined space will change".

This chapter has aimed to de-mystify the complex mathematics and clarify the unnecessary confusion caused by different terminologies used in current literature. Research efforts should now be focused on a number of interrelated areas. First, a better understanding of these distortion techniques from the HCI perspective should be aimed at by gathering empirical evidence to evaluate the usability of these interfaces. Evaluation of graphical user interfaces is a highly complex task, and a multi-dimensional approach (Burger & Apperley, 1991) is recommended as it provides a comprehensive view for effective interface evaluation. Second, with a better understanding of the usability of these techniques, optimum application domains can then be identified. Third, algorithms or specific hardware architectures should be developed to optimise system response time to enable these techniques to be applied in complex real time situations. Finally, other non-distortion techniques, such as information suppression, should also be investigated further as they are potentially powerful. They could be applied concurrently with the distortion-oriented techniques to complement their effectiveness.

Chapter 5

E³: A Framework for the Metrication of Presentation Techniques for Large Data Sets

"There are uncountable ways of representing information, ranging from drawings of circles divided into wedges to patterns of cracks on tortoise shells to differences in the size of bubbles in a fluid.... A display will be effective when it takes advantage of the capabilities of our perceptual, memory, and conceptual abilities; an optimal graphical display for a human might not be optimal for robots or creatures from other planet."

Kosslyn, 1985

Whilst researchers have developed many novel techniques to overcome the problems associated with the presentation and navigation of large data sets, the choice of a technique in a particular application remains very subjective. This chapter proposes an evaluation framework which aims to provide a basis for the comparison of different presentation techniques, given the nature and characteristics of the data to be presented, and the interpretation required. Section 5.1 highlights the problem facing the interface designer in the selection of a presentation technique for the display of large data sets. Section 5.2 examines the issues involved in representing and presenting these data sets. The E³ evaluation framework is then presented in Section 5.3 and a detailed discussion with illustrative examples is provided in Section 5.4. Section 5.5 points out some of limitations of this framework and identifies further work to be carried out.

5.1 Introduction

Graphics has long been exploited to represent abstract quantitative data, since William Playfair published his *Commercial and Political Atlas* nearly two hundred years ago. Graphical charts and plots are now standard tools in presenting statistical data; they are superior to tables of numerical values by being more compact and aesthetically pleasing, and by their ability to attract viewers' attention and convey the underlying information quickly. There is research evidence in experimental psychology and cognitive science to suggest that well designed graphics aid comprehension, decision making and recall (Larkin & Simon, 1987). Conversely, poorly prepared graphics misrepresent the inherent data and mislead the viewer. Considerable skills and experience are required to design effective graphics to achieve optimal visual communication. Fortunately, well established guidelines are available for designers to exploit the potential of this powerful medium to the fullest (Bertin, 1983; Chambers, Cleveland, Kleiner & Tukey, 1983; Fisher, 1982; Schmid, 1983; Tufte, 1983, 1990).

With the advent of video display units, the use of computer generated graphics to present information has grown at a phenomenal pace since Ivan Sutherland embarked on his SKETCHPAD project (Sutherland, 1963) three decades ago. The enormous computational power of personal computers available these days has made them ideal vehicles for presenting graphical information, not only statically, but also dynamically. Sophisticated user interfaces have been developed relying principally on the use of computer graphics. Nowadays, a typical graphical user interface enables the user to manipulate directly any object or item of interest on the display screen. The high resolution of the graphics monitor coupled with a near instantaneous system response time provides the user with a feel of realism and complete control.

At the same time advances in communications and computer technologies over the past decade have provided users with greater access to large volumes of data from computer-based information systems. This trend is set to continue as ever improving networking facilities and transmission rates enable greater connectivity to an expanding range of remote databases. This increasing facility for information access has the potential to improve operational efficiency and provide high productivity in a business environment. However, these advantages will only materialise if users of these computer-based systems can operate and manage this information explosion effectively.

The issue addressed in this chapter relates to the problem of accessing large data sets via relatively limited display surfaces. Whilst researchers (Spence & Apperley, 1982; Furnas, 1986; Leung, 1989; Card et al, 1991; Mackinlay et al, 1991; Sarkar & Brown, 1992) have developed a variety of novel techniques to overcome these

problems, the choice of a technique for a particular application remains very subjective. This is partly attributable to the fact that current evaluation methodologies for these techniques, particularly those pertaining to spatial data and/or involving geometric transformations, are inadequate. Furthermore, there are many system-specific parameters related to these techniques making generalisation of experimental results very difficult, if not impossible. This chapter proposes a framework E³ which aims to provide a basis for the comparison of different presentation techniques, given the nature and characteristics of the data to be presented, and the interpretation required. E³ focuses on three aspects of graphical data presentation: *expressiveness*, *efficiency*, and *effectiveness*. (Throughout this chapter, the use of any of these three words in the context of E³ is italicised.) It is suggested that this framework could lead to the development of a set of metrics to facilitate an objective assessment of presentation techniques, and the choice of an appropriate technique for a given circumstance.

5.2 Presentation of Large Data Sets

The front end of a user interface is what the user sees on the computer screen. In designing interfaces for large data sets, much effort has been placed in perfecting the presentation of the data for optimal visual communication. However, this can be achieved only if the designer has a thorough knowledge of the capabilities and limitations of the hardware at hand, a good understanding of the nature of the data to be presented, and an insight into the potential mental operations that the user performs on the data. The following subsections describe in detail the three key areas of consideration in the course of designing and implementing graphical user interfaces for large data sets - classification, representation and presentation.

5.2.1 Classification of Data Types

Whilst digital computers represent and store information in binary form, where each piece of data is encoded in a string of 1s and 0s, data can be classified in a variety of ways depending on the perspective to be taken. Stevens provided a useful classification of data in the context of measurement (Stevens, 1946); the four measurement scales of data proposed are nominal, ordinal, interval and ratio. In the context of presentation, data can be broadly classified according to whether it is inherently graphical in nature, with implicit spatial relationships, or whether it is non-graphical. In many cases, however, data of the latter type can be represented in an abstract graphical form (Figure 4.1).

The way in which a piece of data is stored in a computer is similar to that in which a folder is put away in a personal filing system. An orderly, and often hierarchical, structure must be in place to allow speedy data deposits and retrievals. In the case of a collection of unstructured data, it may be ordered arbitrarily; for example, the data set may be sequenced by an alphabetical index or by the data's physical size. Data sets with an inherent linear structure may be organised as link lists. Pieces of data are often conveniently grouped together to form a single unit of information or a record; for example, a student has a name, an ID number, an address and a list of enrolled subjects, etc. These units of information may in turn be grouped together to form a hierarchical tree structure with multiple levels depending on the size and complexity of the data set. It is interesting to note that an orderly data structure not only allows speedy system access but also enables the viewer to establish and maintain a conceptual model of the data set; the latter advantage is particularly beneficial for large data sets. To facilitate the process of constructing such a model, various levels of abstraction may also be applied to represent the underlying data in the hierarchical structure.

5.2.2 Representation of Data

A set of data may be represented graphically in a number of ways. Students' performances in a class test may be presented by a standard bar chart with the x axis showing the grades and the y axis the number of students; the length of bar represents the number of students achieving a particular grade. Similarly, a pie chart could have been used with sections of the pie chart representing the number of students in each of the grades. The choice of a particular representation method usually depends on the information intended to be conveyed, and the mental operations the viewer is likely to perform on the information presented. In the previous example, if the user wishes to extract proportion information relating to the population quickly, a pie chart will be more appropriate. On the other hand, if the user is more interested in comparing two exemplars, a bar chart will be superior. Much experimental work has been carried out to study the perceptual properties of a wide range of representation techniques, and there are well established guidelines available to designers (Bertin, 1983; Chambers et al, 1983; Fisher, 1982; Schmid, 1983; Tufte, 1983, 1990). These guidelines enable the designer to match the specific perceptual tasks carried out by the viewer, with the most appropriate representation method. Furthermore, many novel representation techniques, for example using cartoon faces (Chernoff, 1973), stars (Goldwyn et al, 1971), glyphs (Anderson, 1960), trees and castles (Kleiner & Hartigan, 1981), have been invented to represent multi-dimensional data.

It should be pointed out that the encoding process involved in data representation often reduces the precision of the underlying data. Precision, however, is not always desirable; although a table of numbers contains highly precise numerical data, it requires much mental effort for the viewer to extract useful information from it. In many applications, viewers do not require data accuracy to the level of numerical values, and they would willingly trade such accuracy for reduced cognitive load in locating and interpreting the data.

In a large hierarchical data set, abstraction serves as a useful means for information hiding, enabling the viewer to visualise the global structure of the data set. Such data sets are represented in an abstract form primarily to save space as the display surface is limited in size. In a multi-level hierarchical data structure, different degrees of abstraction may be applied at each level, and due design consideration must be given to ensure consistency in representation.

5.2.3 Presentation of Data

Despite the large variety of computer-based information systems and their wide span of application domains, there are fundamentally three functions which a user performs when interacting with such a system: (i) locating an item of interest in the data set, (ii) interpreting the data, and (iii) relating an item to other data in the set. Over the years, user interface designers have expended much effort in producing 'easy-to-learn' and 'easy-to-use' human-computer interfaces for large data sets, to enable the user to carry out these three operations. Although experimental psychologists and cognitive scientists have made much progress in the understanding of the human visual system, presentation of data, especially large data sets, remains the most challenging aspect of an interface design.

A major problem associated with the presentation of large data sets is the relative small window through which an information space can be viewed. A consequence of this 'keyhole' effect is that the user is unable to relate the current view on the display surface with the overall context of the data structure, thus giving rise to the 'where am I?' problem. This undesirable effect may be ameliorated or eradicated by using special presentation techniques.

Whilst presentation techniques can be broadly classified as non-distortion- and distortion-oriented (Leung and Apperley, 1993c), there are generally two approaches in presenting information from large data sets, as shown in Figure 5.1. The first approach (Figure 5.1a) is to reduce systematically the size of the data set to the extent where the desired data can be adequately displayed on the computer screen. In a typical

implementation of this approach, the user is prompted by the system either through a query language or a menu selection process, to specify the subset of the large data set which is of interest. For example, in a financial database application, the system might ask the user a series of questions relating to the particular year, division and department required before presenting the information specified. By restricting the amount of data to be presented, the subset of data can be entirely accommodated on a limited display surface. Hence, presentation no longer remains an issue, and the problem reduces itself to one of data representation.

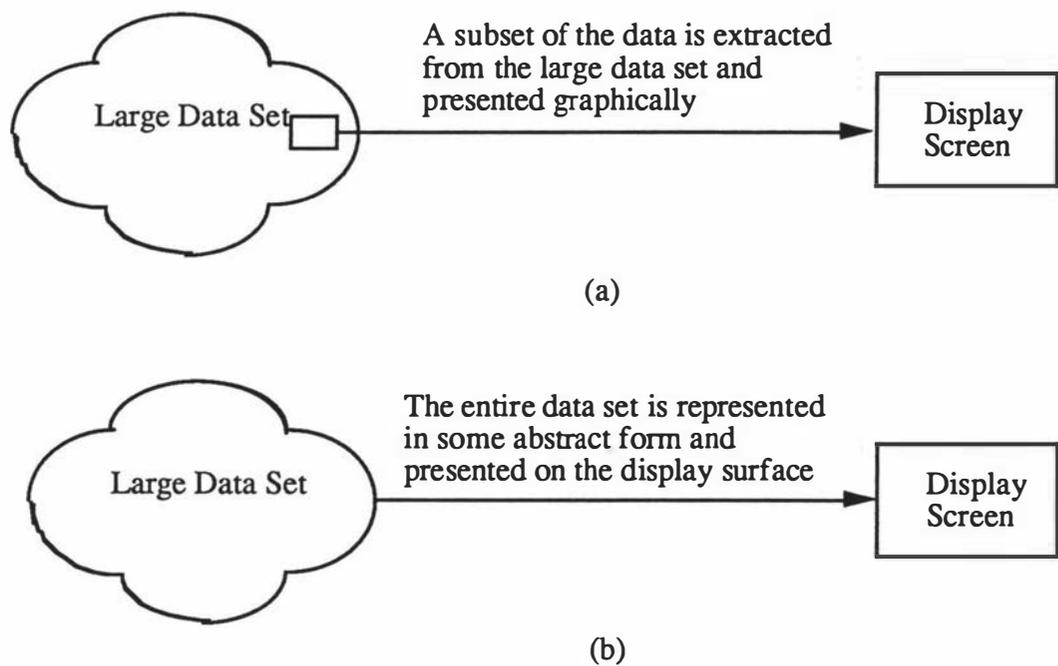


Figure 5.1 Two common approaches in presenting large data sets

This approach is very popular in many PC-based applications because of its simplicity in implementation. In recent years, intelligent and sophisticated systems enabling automatic presentation of small data sets which can fit well in a single window have been developed (Mackinlay, 1987; Casner, 1991; Roth & Mattis, 1991). When applied to a section of a large data set, this approach can be described as a non-distortion

oriented technique, and is most suited to applications where the user has well-defined goals and a good understanding of the internal structure of the data.

The second approach for presenting a large data set, and one which is particularly suitable for spatial data applications, is to represent the entire data set through an abstraction or geometric transformation process (thus reducing its size) and then to display the transformed image of the data set on the computer screen (Figure 5.1b). This approach can be described as a distortion-oriented presentation technique; the user is provided with a complete, but distorted, view of the data set. Commonly this will combine an overview of the structure of the large data set and at the same time, the user is able to examine a small section of data in detail. Figure 4.1, gives a summary of the implementation strategies for distortion- and non-distortion-oriented presentation techniques for different types of data.

Depending on the complexity and the size of the data set, special navigation techniques may have to be devised and implemented to provide adequate global context. This presentation approach is most suitable for browsing where the user may not have a well-defined goal and has very little familiarity or pre-conceived idea of the internal structure of the large data set. When interacting with a new computer-based information system, novice users generally spend much of their time in exploration - casually and often aimlessly moving from one section of the large data set to another. As the user gains experience and becomes familiar interacting with the system, a refined conceptual model of the system is gradually developed.

5.2.4 Presentation Evaluation

In recent years, there has been a growing interest in the development of novel techniques focusing on distortion-oriented presentation approaches as larger databases are becoming more accessible to users. Evaluation of these techniques has tended to be subjective in nature because objective evaluations pose a practical problem that an element of luck may affect the task completion times. This problem, however, may be overcome by conducting an extensive evaluation involving a great number of subjects. However, because of the time and effort constraints, an exhaustive evaluation is often not possible. Even if an exhaustive objective evaluation is made to compare user performance with these interfaces, there is an additional problem of generalisation of results. Distortion-oriented presentation techniques have various system-specific parameters which are different from technique to technique, making a comparison of like-with-like impossible. An evaluation of these techniques using conventional methodologies would, at best, conclude that one interface was better than the other under

the test conditions with the system parameters used. Further generalisation than this runs into the danger of conjecture. A multi-dimensional approach (Burger & Apperley, 1991) to interface evaluation consisting of critical, subjective and objective evaluations, is often desirable as it provides the designer a richer overall picture of the strengths and weaknesses of an interface. Critical evaluation involves the comparison of the user interface design with established, or generally accepted, design principles. The proposed framework E³ complements this approach to enable more objective critical evaluation of interfaces.

5.3 E³ : the Framework

Mackinlay proposed A Presentation Tool (APT), which was primarily intended for small data sets, to automate the design of graphical presentations of relational information (Mackinlay, 1987). He identified two graphic design criteria: expressiveness and effectiveness; the former criterion is associated with graphical languages that express the desired information while the latter is concerned with the most effective graphical language to exploit the capabilities of the output medium and the human visual system. In his framework, graphical presentations are sentences of graphical languages that have precise syntactic and semantic definitions. If a graphical sentence is able to (i) encode all the facts in the set and (ii) encode only the facts in the set, the set of facts is said to be expressible. Effectiveness relates to the ranking of a presentation based on accuracy and perceptual tasks. Whilst Mackinlay's framework is appropriate for his APT system, which is concerned with static presentation of small sets of graphical data, a more generalised framework for a wider application domain covering large data sets is desirable.

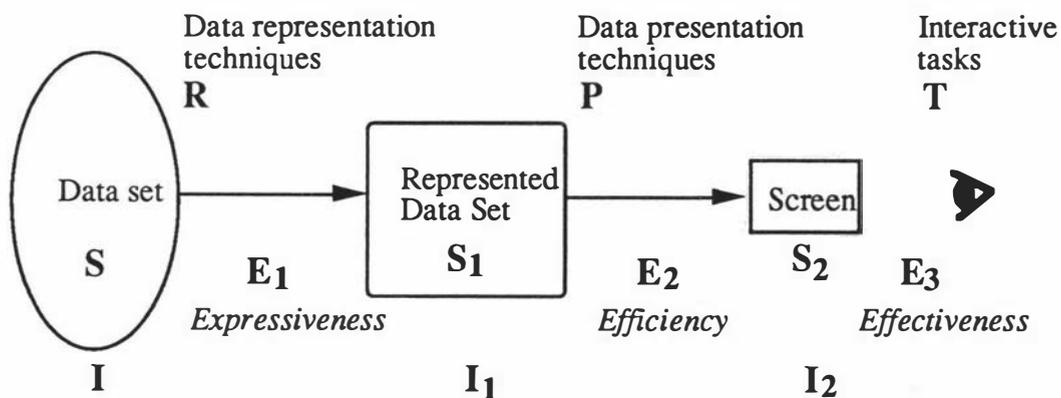
E³ focuses on three aspects of graphical data presentation: *expressiveness* (E₁), *efficiency* (E₂) and *effectiveness* (E₃). Various components of the framework are illustrated in Figure 5.2, showing the notations used, their relationships and the stages involved in designing a presentation system for large data sets. It should be pointed out that because of the differences in the approach adopted in developing E³, the interpretation of the terms *expressiveness* and *effectiveness* used is different to that of Mackinlay (1986). In E³ the original data set **S** is transformed to a representation **S₁** through an abstraction process selected from a set of representation techniques **R**. The represented data set **S₁** in turn is transformed to **S₂**, the data set to be presented on the screen; a set of presentation techniques **P** is available to support this transformation. Consider the flow of information from one point to another in the framework. The

amount of information contained in the sets S , S_1 , and S_2 are I , I_1 , and I_2 respectively. The information flow from I to I_1 is closely related to *expressiveness* and that from I_1 to I_2 *efficiency*. I_1 and I_2 can be given by the functions,

$$I_1 = F_1(E_1, I, R)$$

$$I_2 = F_2(E_2, I_1, P)$$

Effectiveness, however, deals with the overall information flow from the original data set to the viewer. Whilst information is invariably lost in these transformation processes, E³ helps to identify and relate the cause to a particular aspect of the presentation. The following subsections provide a detailed explanation of the mathematical framework showing the relationship of the key E³ components.



Legend

I	information content in S	P	set of presentation techniques
I_1	information content in S_1	R	set of representation techniques
I_2	information content in S_2	S	set of original data
		S_1	set of the abstracted data
		S_2	set of the data presented
		T	set of interactive tasks

Figure 5.2 Stages involved in designing a presentation system for large data sets

5.3.1 Expressiveness

Expressiveness (**E₁**) in the E³ framework is defined as the ability of a representation technique to encode the underlying data accurately and consistently. It can be given by the function,

$$E_1 = F_R(S, R)$$

There are two aspects of *expressiveness*. The first aspect relates to Tufte's concept of a Lie Factor (Tufte, 1983) which is defined as,

$$\text{Lie Factor} = \frac{\text{Size of effect shown in graphic}}{\text{Size of effect in data}}$$

The Lie Factor (LF) provides a quantitative measurement of graphic misrepresentation; the graphic representation is perfect with a Lie Factor of 1. Tufte further suggests that the logarithm of the Lie Factor can be used as a means to compare overstating ($\log LF > 0$) with understating ($\log LF < 0$) errors. In print media, graphic exaggerations are sometimes used on purpose to attract the attention of the reader. Such misrepresentation can be easily eliminated by proper encoding of the data.

The second aspect of *expressiveness* relates to the human visio-perceptual capability. Cleveland & McGill's research on graph perception (Cleveland & McGill, 1984) provided an accuracy ranking order of ten encoding techniques for quantitative data which Mackinlay later (1987) extended to include ordinal and nominal data. These rankings help to identify the degree of information loss resulted from the representation technique selected.

5.3.2 Efficiency

Efficiency (**E₂**) is defined as a ratio of the amount of information presented data on the display surface (**I₂**) to that in the represented data set (**I₁**),

$$E_2 = F_p(I_1, I_2) = \frac{I_2}{I_1}$$

The concept of presentation efficiency bears a philosophical semblance to Tufte's data-ink ratio (Tufte 1983 p.93). One of Tufte's principal graphic design guidelines is that the share of data-ink should be maximised (other relevant matters being equal). The data-ink ratio is given by the following expression,

$$\begin{aligned} \text{Data-ink ratio} &= \frac{\text{data-ink}}{\text{total ink used to print the graphic}} \\ &= 1.0 - \text{proportion of a graphic that can be erased} \\ &\quad \text{without loss of data-information} \end{aligned}$$

In E³, *efficiency* will normally be 100% for small data sets where the entire S₁ can be adequately accommodated on the display screen. In the case of large data sets, this is often not the case. The proportion of S₁ presented on the display screen is therefore presentation *efficiency*.

5.3.3 Effectiveness

Effectiveness (E₃), which is an overall measure of how effective a presentation is, is dependant on the other two criteria, *expressiveness* and *efficiency*, and the set of interactive tasks performed by the user. It can be given by the function,

$$E_3 = F_E(E_1, E_2, T)$$

Expressiveness and *efficiency* affect the overall *effectiveness* of a presentation as these two presentation criteria directly determine the information flow from the original data set to the user. *Effectiveness* is task-oriented; the nature of the tasks performed by the user affect significantly a system's *effectiveness*. Further, the selection of representation and presentation techniques for a particular application is primarily made with due consideration of the three fundamental user tasks: locating, interpreting, and relating.

5.4 Discussion

In the following subsections, two applications of E³ are examined to illustrate how the framework may be applied to practical situations. In the first example, the presentation of a spatial information system, the London Underground Map, is considered using two different presentation techniques (Figures 3.7 and 3.6a), simple windowing and the Bifocal Display (Spence & Apperley, 1982; Leung, 1989). In this case, the original data is in graphical form. For the simple windowed display (Figure 3.7), only a rectangular sub-section of the map is seen. However, with the Bifocal Display (Figure 3.6a), the entire map is shown, albeit with some areas distorted. In the second example (Figure 5.3), the presentation of data from a spreadsheet using two

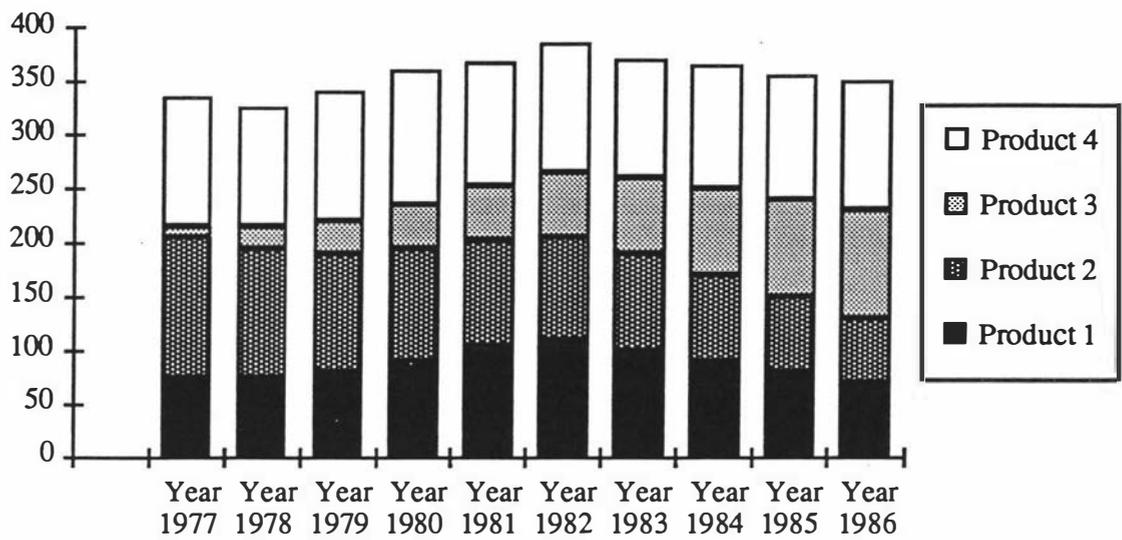
representation methods, one based on position and the other on length, is investigated. The spreadsheet, which consists of sales data of four products over a ten year period, is taken from experimental work on the appropriateness of alternative forms of graphical data presentation (Sparrow, 1989). The original data is in numeric form (Figure 5.3a), and is represented as either a stacked bar chart (Figure 5.3b) or a multiple line graph (Figure 5.3c). In either case, the graphical form is not large, and may be readily displayed on the screen in its entirety.

5.4.1 Expressiveness

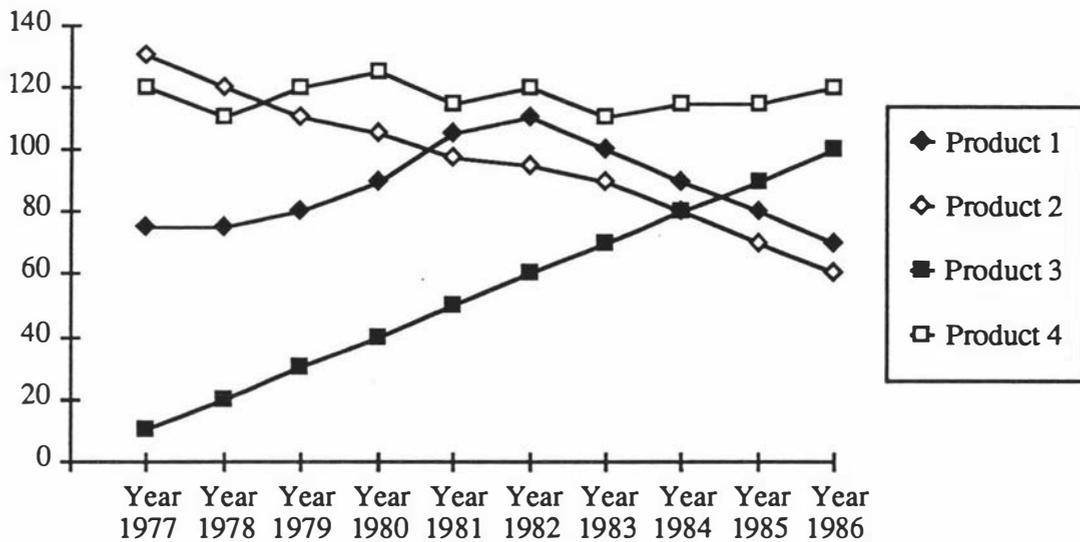
As defined in E³ (Figure 5.2), *expressiveness* is (E₁) a measure based on the nature of the data and its representation. Because of the graphical nature of the data inherent in the spatial information system, direct representation is involved and no additional data encoding takes place in the simple windowing presentation; *expressiveness* for the simple windowing presentation is therefore maximum (1). However, as station names are suppressed in the out of focus regions of the Bifocal Display, *expressiveness* (E₁) for the Bifocal Display can only be close to this maximum value.

Sales figures					
Year	Product 1	Product 2	Product 3	Product 4	Total
Year 1977	75	130	10	120	335
Year 1978	75	120	20	110	325
Year 1979	80	110	30	120	340
Year 1980	90	105	40	125	360
Year 1981	105	97	50	115	367
Year 1982	110	95	60	120	385
Year 1983	100	90	70	110	370
Year 1984	90	80	80	115	365
Year 1985	80	70	90	115	355
Year 1986	70	60	100	120	350
Total	875	957	550	1170	3552

(5.3a)



(5.3b)



(5.3c)

Figure 5.3 Example diagrams as used by Sparrow (1987). (a) The spreadsheet of the original sales data used in Sparrow's illustrations; (b) representation of the data set based on length in a stacked bar chart; and (c) representation of the same data set based on position in a multi-line graph.

In the spreadsheet example (Figure 5.3), the *expressiveness* of the two representation techniques may be compared according to the accuracy of the encoding methods used, based on human visio-perceptual capabilities. According to Cleveland & McGill's relative ratings (Cleveland & McGill, 1984), the position representation (line graph) of this quantitative data set is one rank higher than the length representation (bar encoding chart) in terms of *expressiveness*. It is interesting to note that the superiority of position encoding is more prominent in ordinal and nominal data according to Mackinlay (1987).

5.4.2 Efficiency

Efficiency (E_2) is defined as the proportion of the represented data set which may be presented on the display screen at one time. In the spatial data example, the *efficiency* of the Bifocal Display for the London Underground map is close to 100% as the entire representation (although distorted and with the suppression of station names in the out-of-focus regions) is displayed; S_2 is close to S_1 (Figure 5.2). With the simple window presentation technique for the same map, however, the *efficiency* is calculated as follows:

$$\text{Efficiency } (E_1)_{\text{windowing}} = 0.4 \text{ (width)} \times 0.5 \text{ (height)} \times 100\% = 20\%$$

In the spreadsheet example (Figure 5.3) all of the data is displayed, and because S_1 is the same as S_2 , the *efficiency* is 100%.

5.4.3 Effectiveness

As mentioned previously, in E³ *expressiveness* is data dependent while *effectiveness* is task dependent. Assessment of the relative *effectiveness* should therefore be based on the underlying tasks performed by the user. In an experimental investigation of report formats and the decision maker's task conducted by Davis (1989), subjects were asked to make various decisions based on financial information presented in four forms: line graph, bar chart, pie chart, and table. Davis concluded that the most appropriate method of presenting financial information is dependent on the decision maker's question and that graphical presentations result in better performance only when they provide specific visual cues with aid in the answering of a question.

In the context of the London Underground map, the user may wish to search for a station and plan a route using station-related information as search keys; the search keys may be in the form of station name, general position in the map, proximity to a landmark station, the colour of the railway line or the intersection of two lines. A critical

evaluation of these tasks (Leung, 1992) suggests that the Bifocal Display is superior to simple windowing for a search key with station name and proximity information, while the reverse is true for a search key with information about the intersection of two lines.

Six types of information have been identified by Sparrow (1989) as most commonly required by users of spreadsheets. They are information about specifics, limits, conjunction, accumulation, trends and proportion. Two of the tasks investigated in Sparrow's experiment are considered here. One is concerned with identifying the year when a product's sales was the highest or lowest (information about limits), and the other involves determining the year when one product sold less than another (information about conjunction). In the spreadsheet example, Sparrow found that overall, the stacked bar chart was more effective for assessing limits (about twice as good based on error rate). However, the multiple line graph was superior for conjunction and trends assessments.

	Spatial Data Example			Numerical Data Example		
	Window	Bifocal		Bar Chart	Line Graph	
E₁	1	~1		x	y	(1 > y > x)
E₂	0.2	~1		1	1	
E₃	specific	a < b	limits	e > f		
	intersection	c > d	conjunction	g < h		

Figure 5.4 A summary of analysis of the two examples. x, y, a, b, c, d, e, f, g and h are numbers between 0 to 1 inclusive, used here for comparative purposes.

5.4.4 General Comments

The analysis of the two examples is summarised in Figure 5.4. The constants x , y , a , b , c , d , e , f , g and h , valued from 0 to 1 inclusive, are arbitrary figures used here for comparative purposes in the E³ framework. It should be pointed out that screen resolution influences the *effectiveness* and not the *efficiency* of a presentation as defined in E³. Further, it is possible that a system may have high *expressiveness* and *efficiency* ratings, but due to implementation inadequacies such as poor screen resolution, a low *effectiveness* rating results.

The two examples above show how E³ may be applied in the comparison of graphical interfaces for two typical information systems. It is apparent that the three graphic criteria, *expressiveness*, *efficiency* and *effectiveness* impinge on each other. It is often not possible for a design to yield maximum ratings in all three criteria, as these criteria generally place competing demands on the limited system resource. A good interface design would, therefore, be the one which compromises these criteria to yield the optimal result in achieving the desired goals. It should be emphasised that whilst E³ provides the designer with a better understanding of an interface and may also serve as a useful design guide, E³ does not offer a recipe for how these criteria should be compromised.

5.5 Concluding Remarks

This chapter proposes an analytical framework E³ for evaluating presentation techniques for large data sets. E³ also serves as a useful guide for the designer to focus attention on the three graphic criteria when designing these types of interfaces. However, one area which the current framework does not address is the dynamic interaction aspect of the interface with implications on system response time and input device characteristics.

It will be of great value to the interface designer if a set of metrics for presentation techniques is available for an objective evaluation of interfaces in different applications. Whilst E³ has provided the necessary groundwork for metrication, further work is required to extend the current framework to achieve this goal.

Chapter 6

Designing the InfoLens

"Getting information from a table is like extracting sunlight from a cucumber."

Farquhar & Farquhar, cited in Kosslyn, 1985

The lens metaphor has recently been used by various researchers to describe their strategies in overcoming the inherent problem associated with the viewing of large information spaces (Robertson & Mackinlay, 1993; Rao & Card, 1994; Stone, Fishkin & Bier, 1994). This metaphor is based on the familiar concept of a magnifying or photographic lens where the user can intuitively apply its functionalities to the large-world-small-screen situation. This chapter extends the lens metaphor and builds on the theoretical frameworks for visualisation established in earlier chapters. The design of an effective visualisation tool, the InfoLens, is then proposed and issues relating to its implementation are discussed.

In section 6.1, various aspects of the lens metaphor are discussed in detail and its key concepts are brought together and analysed. An extension of this metaphor is then presented. This extension is based upon the adjustment of the focal length of a photographic lens to allow the user to obtain the clearest possible view of the data under consideration. Section 6.2 presents the design rationale of the InfoLens which has been developed using this extended lens metaphor. Section 6.3 shows the prototypes of the system with one- and two-dimensional illustrations of the InfoLens and demonstrates how the InfoLens may also be used to support decision making tasks. In section 6.4

issues pertaining to the implementation of this visualisation tool are discussed. The final review section (6.5) summarises the design of the InfoLens.

6.1 The Lens Metaphor

Learning by analogy is one of the basic approaches to learning; indeed Anderson (1983) argues that this may be the only way that humans actually learn. Whilst user interface designers strive to develop easy-to-learn and easy-to-use interfaces, effective analogies and metaphors have a clear role to play in conceptualising interface design. Interface metaphors are a powerful means to control the complexity of user interfaces; a good example of this is the desktop metaphor which has been very successful in many recent computer systems. In this metaphor the screen resembles the surface of a desk. Files are transformed into pictorial representations such as icons which can be easily identified and understood by the user. This basic conceptual mapping of real objects to their representation on the screen provides the user with the knowledge to interact with these icons. The interface is designed so that equivalent actions can be carried out intuitively on the electronic version. Arguably, this metaphor has revolutionised the design of personal computer systems in recent years.

Carroll, Mack and Kellogg (1988) consider that interface metaphors exploit specific prior knowledge that users have of other domains. Instead of reducing the absolute complexity of an interface, a metaphor seeks to increase the initial familiarity of actions, procedures and concepts by making them similar to actions, procedures and concepts that are already known. Interface metaphors can, therefore, be considered a useful means available to the users for articulating mental models.

Metaphors should not be considered good or bad descriptions of their targets; rather they should be appraised as to their effectiveness as invitations to see a target domain in a new light (Black, 1979; Tourangeau & Sternberg, 1982). Carroll et al (1988) further point out that metaphors, by definition, invariably provide imperfect mappings of their target domains. The inevitable mismatches of the metaphor and its target are a source of complexities for users and their implications should be identified so that design strategies can be formulated to help users manage them.

The magnifying lens has been used by various researchers as a convenient analogy to show how large information spaces can be viewed or assessed. Furnas (1986) proposes the idea of a fisheye lens in viewing large source program codes and tree-structured data. His approach would probably be more appropriately called the logical fisheye lens, as this method relies on selective suppression of information to be

displayed based on a degree of interest function as specified by the user. In a similar vein, Mitta & Gunning (1993) extend Furnas' fisheye lens formalism to complex graphical data where the user can select the relevant information to be displayed or suppressed systematically. On a different tack, Malone, Grant, Lai, Rao & Rosenblitt (1989) present their Information Lens, an intelligent system for information sharing and coordination for users working in a collaborative environment. They consider the filtering effect of a lens in screening a large quantity of electronic messages which have no potential use to the user. The Object Lens (Lai, Malone & Yu, 1989) is an extension of the Information Lens and is capable of handling a wider range of information.

The lens analogy used by these researchers bears a remote resemblance to a magnifying lens. Indeed, the formalisms of a true graphical fisheye lens in the

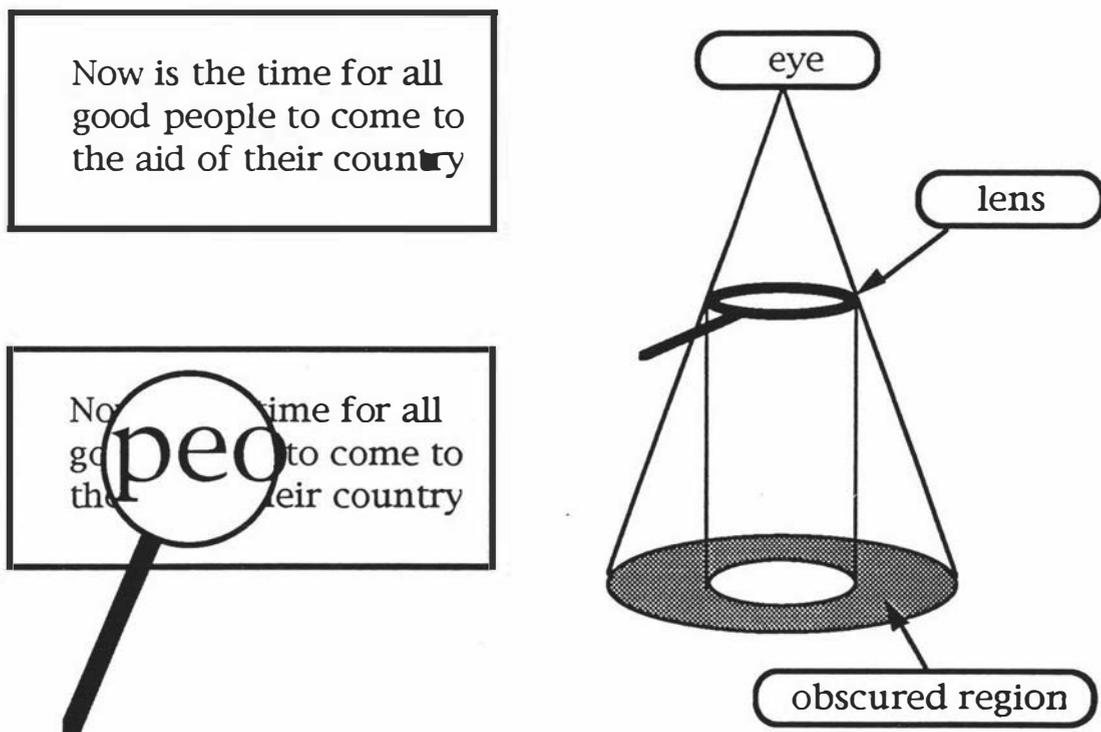


Figure 6.1 The problem with a magnifier lens: parts of the image near the edges of the lens are obscured by the lens. (adapted from Figure 2 of Robertson and Mackinlay's paper)

presentation of graphical data have been proposed rather recently¹ by Misue & Sugiyama (1991) and Sarkar & Brown (1992). Researchers at Xerox PARC have also used the magnifying lens as an analogy to illustrate how large information spaces with different hierarchical structures can be viewed, enabling the user to maintain focus and context. The Document Lens (Robertson & Mackinlay, 1993) has been designed for users to handle information with an unknown structure. It is assumed that the pages of the paper document is to be spread out on a large table where the overall structure and distinguishing features can be seen. The way the user interacts with the Document Lens is similar to the way he or she reacts to a magnifying lens: the user grabs the rectangular lens and pulls it around to focus on the desired area at the desired magnification. The presentation outside the lens is stretched to provide a continuous display of the global context. Building on this fundamental concept, Rao & Card (1994) proposed the Table Lens, a system specifically designed for data which can be arranged as a table, a two-dimensional structure which is commonly found in spreadsheets.

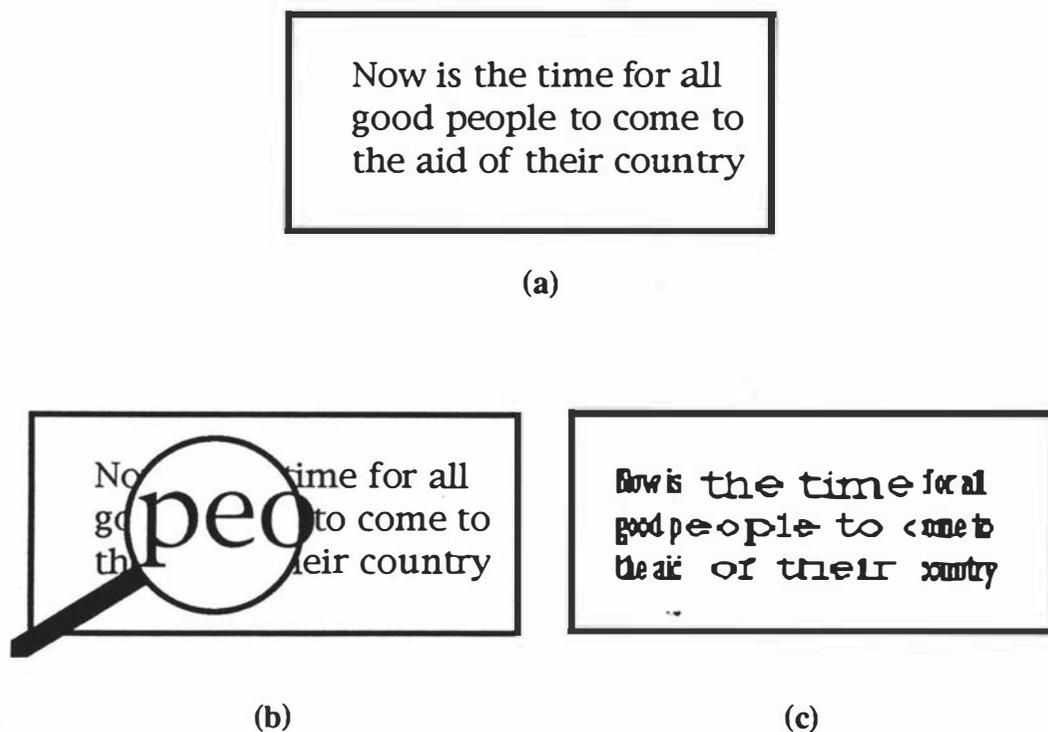


Figure 6.2 An electronic version of a magnifying lens using a one-dimensional Bifocal Display. (a) The original text message; (b) The view of the message using a conventional magnifying lens; and (c) The electronic version of a magnifying lens using a one-dimensional Bifocal Display.

¹ Farrand proposed his DECR (Detail-Enhancing & Context-Retaining) lens (1973) and provided an earlier discussion of the lens concept, but he did not present any formal treatment of this approach.

It is pertinent to explain how the lens metaphor can be applied to the visualisation of large information spaces and the design of the InfoLens. Robertson & Mackinlay (1993) highlight the problem of the conventional magnifying lens in viewing data. Figure 6.1 above, adapted from Figure 2 of their paper, shows that parts of the image near the edges of the lens are obscured by the lens. The area of this obscured region increases, as the lens is moved towards the eye. Figure 6.2 shows the electronic version of a magnifying lens using a one-dimensional Bifocal Display which eliminates this problem.

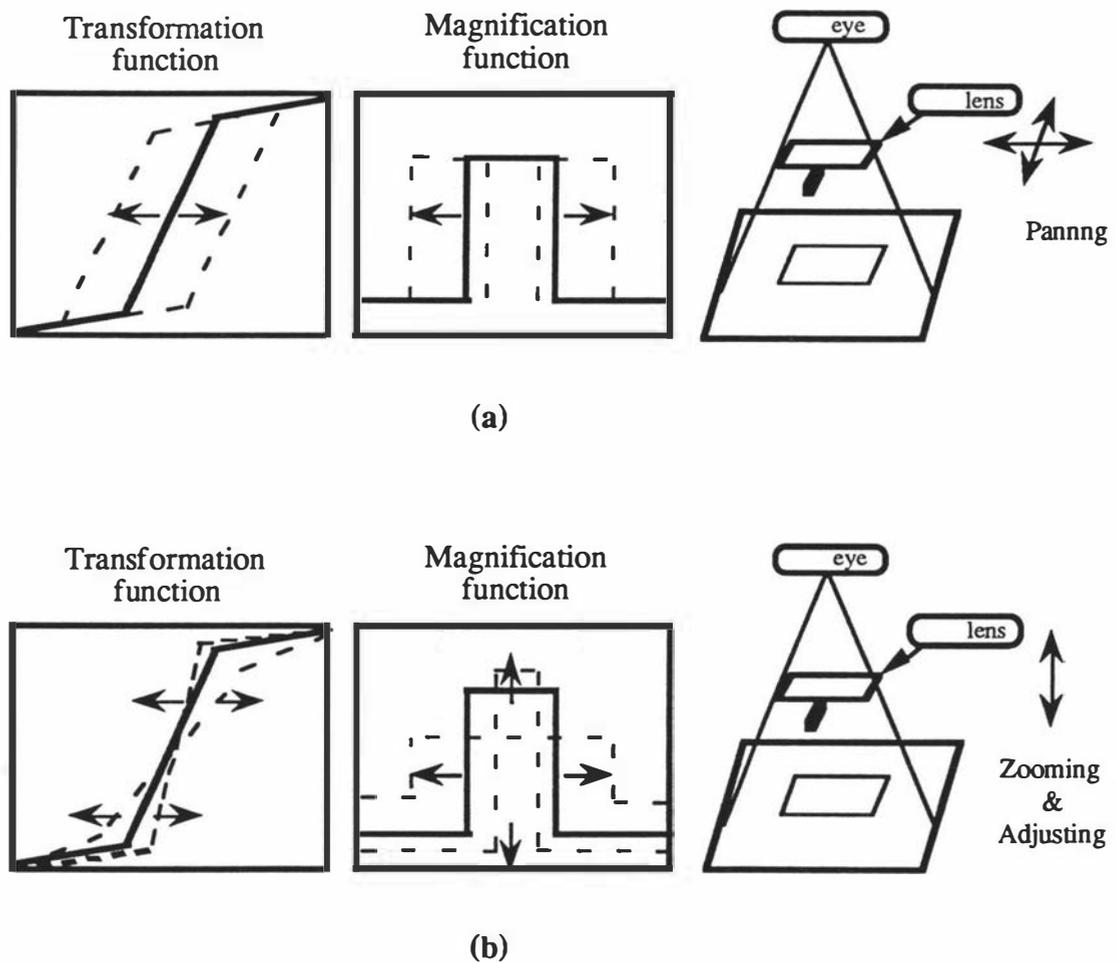


Figure 6.3 The three canonical manipulation operations of a rectangular magnifying lens. (a) The transformation and magnification function of the lens as it is moved horizontally parallel to the plane of the display surface. (b) The transformation and magnification function of the lens as it is moved in a direction perpendicular to the display surface.

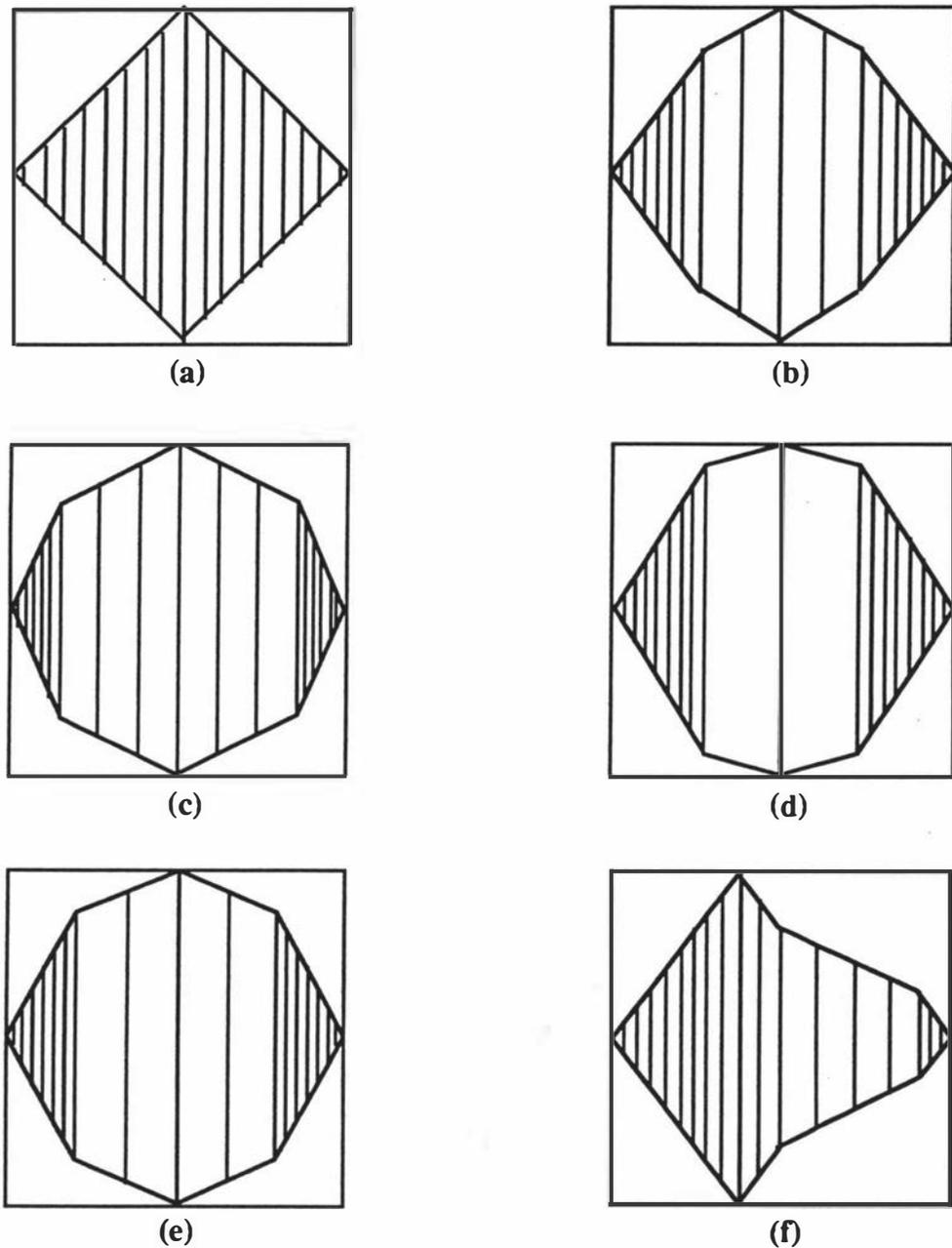


Figure 6.4 Different views generated by manipulating the electronic magnifying lens. (a) The original undistorted image. (b) A one-dimensional Bifocal Display of the image. (c) As the lens is drawn near the viewer, the window for the detailed view is widened while the magnification factor remains unchanged in the focus region. (d) The increase in the magnification factor while the window size remains unchanged. (e) The combined effect of widening the viewport and the increase of the magnification factor in the focus region. (f) The effect of panning to the right the focus region of the one-dimensional Bifocal Display in (b).

The user may move the lens in two ways. First, the lens may be moved freely on a plane parallel to the surface of the displayed information. This has the effect of changing the viewport so that the user can examine a particular area of interest in detail. Second, the user can pull the lens towards (or away from) the eye with the effect of increasing (or decreasing) the display area of the detailed view, at the same time as reducing (or increasing) the size of the out-of-focus view. Another consequence of this action is the zoom-in (or out) effect, where the size of the data displayed within the detailed viewport will be changed. These three canonical operations - zoom, adjust and pan - are the basic forms of manipulations which the user can perform with the lens. Before extensions of these functions are considered, the modification of the conventional magnifying lens is discussed.

Whilst the conventional magnifying lens presents the problem of obscuring part of the information space to be viewed, this can be overcome in implementing an electronic version of the magnifying lens. Transformation functions may be selected for the in-focus and out-of-focus regions, eliminating the obscured region totally. For illustration purposes, in Figure 6.3 the Bifocal Display has been used as the underlying presentation technique for this rectangular lens. The three basic manipulations of this electronic lens may be achieved as it is moved, resulting in a change in the transformation and magnification functions. It is important to note that in the implementation of this electronic lens, there are three possible scenarios when the lens is moved towards the viewer:

- (1) the size of the detailed viewport may increase without any change in the magnification factors in the detailed view; or
- (2) the magnification factors in the detailed view may increase while maintaining the size of the viewport; or
- (3) a combination of (1) and (2) may occur

The conceptual model of distortion-oriented presentation techniques developed in Chapter 4 suggests that if the size of the display area remains fixed, any changes made in the magnification function in one part of the display will be neutralised by compensatory effects in other parts of the display. This zero-sum gain rule governs the operation of the magnification function of the entire display surface. Using a one-dimensional Bifocal Display, Figure 6.4 shows the three possible effects on the entire display as the lens is drawn towards the viewer. Although the lens metaphor has been illustrated using the Bifocal Display, it is important to emphasise that this metaphor is not confined to this technique and other distortion-oriented presentation techniques could be effectively applied.

The lens metaphor described so far only deals with the physical movement of a simple magnifying lens. It does not take into account the fact that in the case of a photographic lens, the user can adjust the focus of the lens freely to obtain the clearest possible image of the data under consideration. In the context of data visualisation, the user typically views the data in a form which enables the user to carry out the task at hand. In the discussion of the E³ metrication framework in Chapter 5, it was pointed out that in a visualisation task, the user interacts with the system to elicit information from it. The information flows between the display screen and the user, who perceives and interprets the relevant data. The representation of data, therefore, is also pertinent to the lens metaphor. If the data is represented in a form which does not facilitate easy performance of a task, the lens may be considered to be out of focus. Data may be represented in various forms with different degrees of accuracy. It is important to reiterate that data accuracy is not always important in a data visualisation task; a table of numbers, albeit highly precise and accurate, is less effective than a line graph if a user wishes to determine the general trend of the data set.

The concept of a lens filter used in photographic lenses may also be considered to extend the lens metaphor further. Lens filters are used by photographers to highlight or bring out important features of an object or a scene. In the context of data visualisation, this lens filter allows the user to view the data selectively. For example, the user may be interested to view the data which fall within a certain range of a large database. In their Magic Lens system, Stone, Fisher and Bier (1994) applied the lens filter metaphor to suppress/display the view of an information space in a way similar to that used by Mitta & Gunning (1992). Stone et al's system is flexible in that the filters are movable and their size may be customised easily by the user. In their HomeFinder system, Williamson & Shneiderman (1992) also used a similar concept to visualise data of an information exploration system.

The magnifying/photographic lens metaphor and its extension described in this section give rise to powerful concepts in the visualisation of large information spaces. These ideas may be brought together to form an integrated visualisation system. Such a system would enable the user to perform a wide variety of tasks such as data exploration and decision making with a large information space. In the following sections, the design of such a system, the InfoLens and its interface is proposed.

6.2 Design Considerations

The lens metaphor and its extension described in the previous section are a convenient framework for dealing with the presentation and navigation problem associated with large information spaces. Certain aspects of this lens metaphor have been used in the design of a general visualisation tool for tabulated data, called the Table Lens (Rao & Card, 1994). The functionalities of a magnifying lens correspond neatly to the typical operations which are performed by a user of a large information space. There are a number of similarities and differences between the Table Lens and the InfoLens, the visualisation system proposed in this research. For example, these two systems tackle the problem of the presenting large information spaces and support different representation of the data sets for various perceptual tasks. Whilst the Table Lens's emphasis is on data exploration, the InfoLens handles both multidimensional data sets and provides the user with additional visualisation functionalities including one which supports decision making. Further, InfoLens also supports data which are inherently spatial in nature, such as map-based diagrams.

The paper describing the Table Lens (Rao & Card, 1994) appeared after the work described in this chapter had been completed. They are parallel developments; the InfoLens is not derived from the Table Lens.

It is important to emphasise that visualisation is a communication process and the primary function of a visualisation tool is to facilitate the data encoding and decoding operations which take place at the interface. One of the primary challenges confronting the interface designer is the selection of a data encoding method which enables the user to decode the data display and to optimise this information flow. The following factors must be considered in detail in the design of the InfoLens.

6.2.1 Data Types

As discussed in Chapter 5, data may be classified in a number of ways. A classification may be made based simply on their appearance. Inherently graphical data are those which have implicit spatial relationships such as topological networks and maps. Non-graphical data are text-based and generally may be conveniently represented graphically to facilitate comparison of data.

A hybrid data system may consist of integrated graphical and non-graphical data. For example, an interactive real time information system of the London Underground Railway System might consist of the map displayed on the screen with numerical data, such as train departure times, embedded under a station symbol.

6.2.2 Data Structure

Hierarchical arrangement is one of the most common solutions used to achieve efficiency in all kinds of dynamic systems (Simon, 1969; Resnikoff, 1989). The visualisation process is a familiar example of an information processing hierarchy: the viewer first sees the overall scene, then the viewer's attention is directed to each individual object and finally to finer attributes of objects.

Whilst data may be organised in a number of ways, they are typically arranged so as to enable specific tasks to be carried out easily. Data with a linear structure are those which can be arranged in one dimension through the use of a sort key. For example, with time-series data where data are ordered chronologically, time is an obvious and convenient key for detecting trends. Two dimensional data types are common with tree and tabular structures as these data structures can also be presented readily on a two-dimensional display surface. Data with a higher order dimension may have to be abstracted or compromised in some way to one- or two-dimensional form so that they can be presented on the screen. The choice of a particular data structure is therefore dependent on the underlying tasks to be performed.

6.2.3 Tasks

As pointed out in the previous chapter, three of the most common data retrieving tasks performed by the user with a database are (i) locating an item of information; (ii) interpreting an item; and (iii) relating it to other items, if it cannot be seen in its full context. Task (i) generally relates to data exploration and tasks (ii) and (iii) require the user to perform varying degrees of decision making operations. Whilst efficient search algorithms are available to ascertain the location of an item of information through the use of search keys, very often the user browses through an information space without a specific aim. Browsing enables the user to gain an overall view of the database in an unconstrained fashion. Although the Table Lens provides the user with an effective means to view the large data set presented on the display screen, the system does not support adequately the performance of tasks (ii) and (iii) in the list above, which are essential in many decision making tasks.

It should be emphasised that the time it takes for the user to perform a task is also dependent on the form in which the data is presented. In the design of the InfoLens, it is important that the visualisation tool is able to support various representations of the data and that it provides the user with facilities to change and select the data format to carry out the task at hand.

6.2.4 Presentation Techniques

Specific presentation techniques are often used to present the data to the user if the space required to display all the data is larger than that available. This space contention gives rise to a navigational problem, where the user, during the course of interaction with the system, may become disoriented or totally lost in an information space. In browsing mode, where the user may explore an information space aimlessly, it is extremely important that he or she can maintain an overall view of this space at all times. Distortion-oriented presentation techniques, which are characterised by their ability to provide the user with a global context as well as local details, are therefore most suitable for this type of application.

Data files come in different sizes and forms which in turn have direct implications for the physical dimensions of the display surface required, if the entire data file is to be displayed. Consequently, the physical size of the display poses a constraint on how efficiently the data can be presented. It is desirable that a presentation technique be flexible to support the diversity of input data files to optimise the use of the display surface. For example, a presentation technique should be adaptable to handle a spreadsheet of 1000 columns and 20 rows as well as one of 1000 columns by 1000 rows, without wasting any screen real estate. The simplicity and flexibility of the one- and two- dimensional Bifocal Displays make it a natural candidate to be the presentation technique used for the InfoLens.

In the design of any presentation system, the size and resolution of the display monitor places an upper limit on the amount of information that can be presented. Although space efficient representation techniques may be used in many situations, interface objects and data presented on the screen do occupy finite area. There is also a limit on the size of the interface objects which may be displayed so that the user can still comfortably see and interact with them. As a general design guideline, Leung (1989) suggests that the application of Bifocal Displays to map-based diagrams should be confined to situations where the size of the diagram is less than 40 times the size of the screen. Non-distortion-oriented presentation techniques, such as the two screen and split screen systems, are more suited for diagrams beyond this limit. In describing their Table Lens system for presenting tabular information, Rao & Card (1994) also suggest that their system, using a scheme similar to the Bifocal Display, can comfortably manage about 30 times as many cells as can normally be displayed on a screen of the same size.

6.2.5 User Interface

It is well recognised that the design of a user interface is a complex task. Myers (1993) provides a comprehensive list of reasons that user interfaces are difficult to design and implement. Despite advances in human-computer interface development, no accepted methodology exists to guide development of the complex structure of an

interface (Hartson & Hix, 1989). Whilst a variety of general guidelines for interface design are available (Rubenstein & Hersch, 1984; Smith & Mosier, 1986; Brown, 1988; Galitz, 1989), they are either too general or too restrictive and often fail to offer a coherent and systematic framework for the designer to tackle a specific problem.

Despite these difficulties, the advent of the desk metaphor has greatly contributed to the standardised look and feel of modern user interfaces. It is important to emphasise that the more consistent the look and feel of interfaces are, the easier and faster it will be for users to transfer their operating knowledge from one system to another. The desktop metaphor is synonymous with direct manipulation interfaces. Shneiderman (1983) suggests that the key features of direct manipulation systems are (1) the visibility of the objects of interest; (2) rapid, reversible, incremental actions; and (3) direct manipulation of the object of interest instead of complex command language syntax.

As the InfoLens is a general visualisation tool, its interface should be designed to cater for all potential users, ranging from the expert to the novice. The lens metaphor is pivotal to the conception of the InfoLens. The effectiveness of this tool is dependent on the interface objects with which the user interacts. These interface objects should be designed to provide adequate visual cues to enable the users to operate this powerful tool. Since the system is primarily graphical in nature, it is expedient to consider a direct manipulation type of dialogue style for the interface to the InfoLens. A mouse or trackball would be an appropriate interaction device to support the range of manipulations required by the user; a touch and pressure sensitive screen may not be as suitable, as the size of the user's finger would constrain the range of tasks which could be carried out. For example, the manipulation of a small cell in the spreadsheet would be difficult with a touch sensitive screen operated by the user's finger.

Commonly available mice have one to three buttons. Increasing the system functionality which may be performed with an interaction device invariably adds to the complexity of the interface and imposes an additional load on the user's cognitive resources. The one-button mouse has been used very successfully in the Macintosh system, even with applications involving complex interfaces. In the design of the InfoLens, it seems expedient, therefore, to take the simplest approach and to consider the use of a one mouse button for the operation of the interface. The single button may be used for the activation of an interface object or to select (with a single click) an item of interest on display. The ability to toggle the state of an interface object with a mouse button also enhances the functionalities of a single button mouse.

6.3 Iterative Design and Illustrations of the InfoLens

This section presents an on-going iterative design of the InfoLens and illustrates the key concepts of the system as a visualisation tool.

6.3.1 The Interface of the InfoLens

Figure 6.5 shows the layout of the interface of the InfoLens. As we are primarily interested in the visualisation aspects of the system, the menu bar at the top of the screen, which mainly supports file manipulation functions, is not described here.

The interface illustrated in Figure 6.5 consists of two distinct sections, the display area of the InfoLens and the controls of the interface. The functionality of these interface components are discussed in turn.

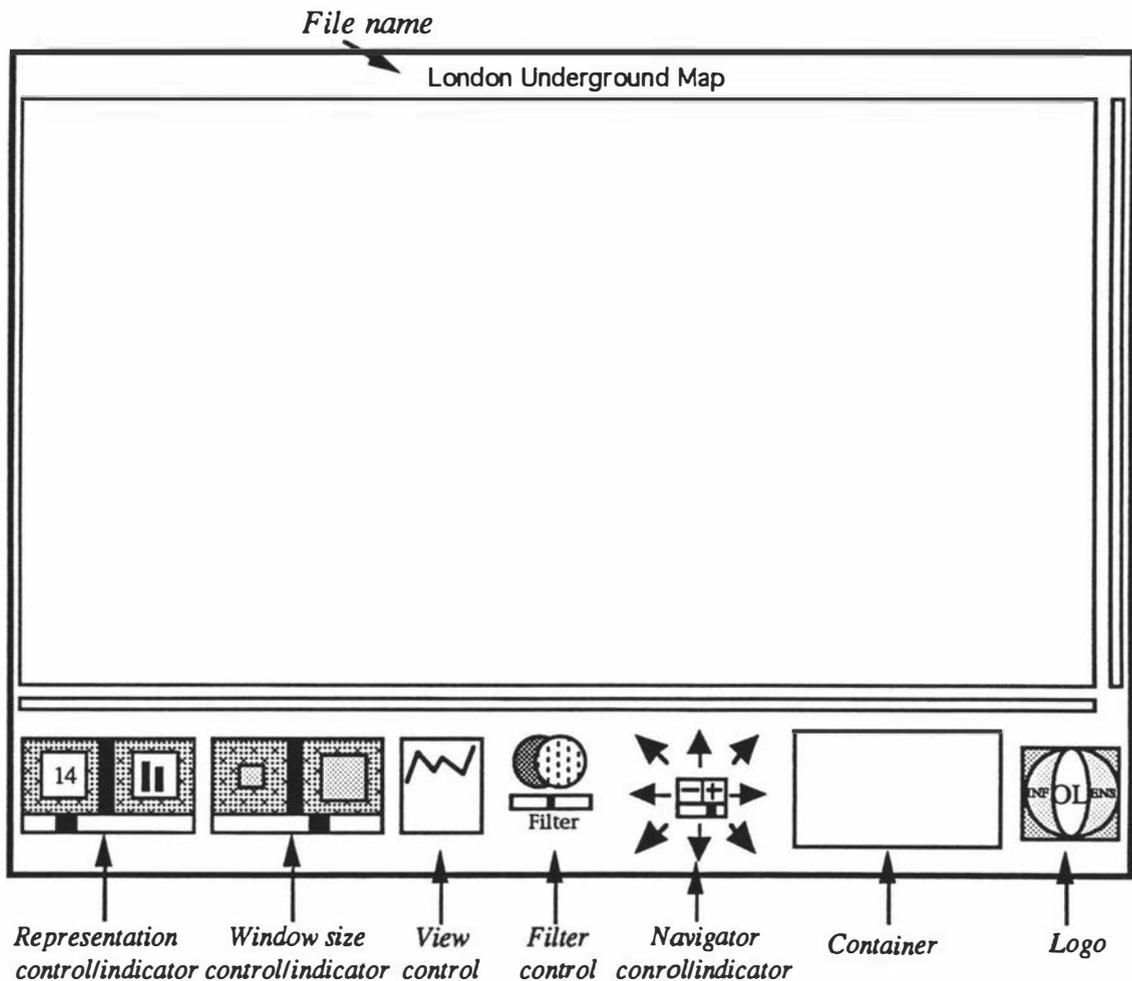


Figure 6.5 The interface of the InfoLens

The data display area

The rectangular data display area of the InfoLens is supported by two scroll bars. Scroll bars, which are commonly used in software applications, are an effective navigation tool to manipulate a large information space; the position markers on the scroll bars indicate the current position of the in-focus view in relation to the entire information space. A specific navigation control is provided under the data display area to support a finer and more flexible manipulation of the in-focus view. Above the display area, the title of the data set is displayed.

The control panel

The control panel consists of a number of buttons and interface objects available to the user to operate the InfoLens. An audio prompt is issued in addition to immediate visual feedback to the user when a selection violation has occurred, for example, the user may have clicked the mouse button outside the icon area. Details of these interface objects as they appear from left to right are discussed below.



Representation control/indicator

This interface object is located at the bottom left hand corner of the display screen. Its appearance and operation resemble the scale factor control used in MacDraw (Claris Corporation, 1988). It provides the user with a convenient means to change the representation (or level of graphical abstraction) of the data in the in-focus area. In the context of the lens metaphor, this allows the adjustment of the focal length of the lens to facilitate a variety of tasks.

This interface object consists of three distinct parts: two square buttons at the top and a scroll bar at the bottom. When the left button area of this object is activated with a mouse, the graphical data abstraction of the data presented decreases by one level; in one extreme case, textual data is presented in the form of a table of alphanumericals. In contrast, activating the right button area results in an increase in graphical abstraction of the data presented; these data representations are provided to facilitate a variety of perceptual tasks. The scroll bar at the bottom of this interface object provides useful visual feedback to the user, as it indicates the current level of graphical abstraction within the available range. For rapid selection of the particular graphical representation, the position marker may be dragged to any desired position within the range of the scroll bar. This operation is augmented by a textual menu displayed underneath the scroll bar to show the current selection and the various representations available. Figure 6.6

shows three different representations of a table of data as this control button is progressively activated. In this illustration, the order of data representations for the scroll bar is based on Mackinlay's (1987) accuracy ranking of quantitative perceptual tasks. The representation control may also be applied selectively within the in-focus area; the data to be operated on by this control must be selected by the user first with a click-and-drag action.

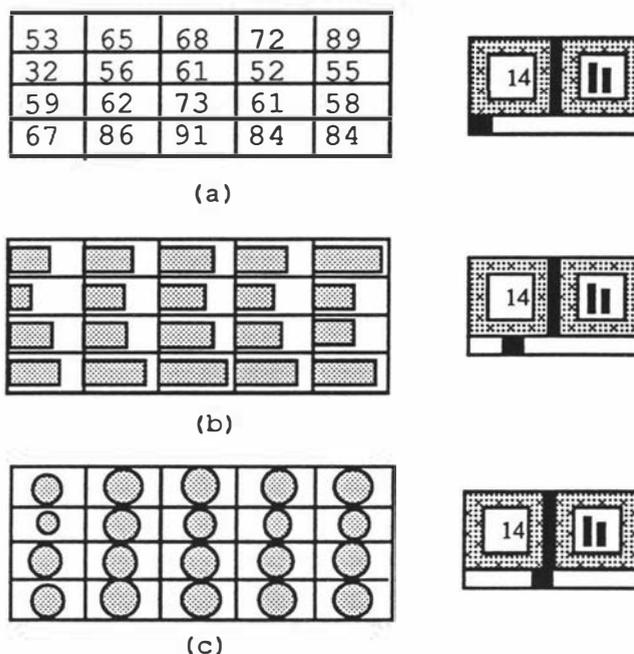


Figure 6.6 Three representations of the data as the representation button is progressively activated: (a) the numerical data; (b) the same data represented by rectangular bars; and (c) the same data represented by areas.

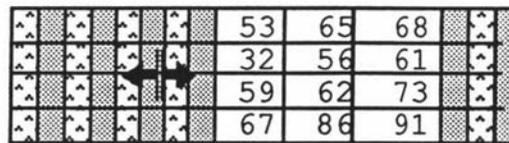


Window size control/indicator

This interface object is similar in appearance and operation to the representation control/indicator. The two buttons on the top of the object allow the user progressively to increase (right button) or decrease (left button) the size of the in-focus region of the display both in the X and Y directions. The size of the rectangle in the button indicates the direction of change. In the context of the lens metaphor, the lens may be pulled towards (to decrease the window size) and away from (to increase the window size) the data under consideration. The bottom scroll bar may also be manipulated in the usual way for speedy change of window size. This operation is augmented by a textual menu

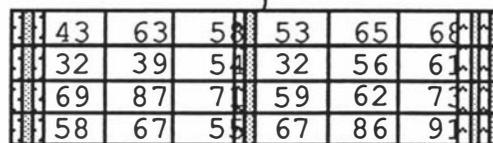
displayed underneath the scroll bar to show the current selection and the various window sizes available.

The size of the in-focus region may also be changed in the X or Y direction independently. As the mouse cursor is moved near any of the region borders, a special cursor  or  appears which enables the user to adjust the column width or row height to show the hidden data in the direction indicated. This cursor may be used in a similar way in the out-of-focus regions to enable a particular demagnified area to be opened up for examination, effectively creating a multiple focus view (Figure 6.7). A section of the table within the in-focus region may be collapsed in a similar manner. When a multiple focus view is generated (Figure 6.7b), any control button activation will have the desired effect equally applied to each of the in-focus regions.



			53	65	68
			32	56	61
			59	62	73
			67	86	91

(a)



43	63	58	53	65	68
32	39	54	32	56	61
69	87	71	59	62	73
58	67	55	67	86	91

(b)

Figure 6.7 The operation of the special cursor for adjusting the column width or row height to show the hidden data. (a) As the normal arrow cursor is placed near a cell border, it changes into a cursor which enables the user to adjust the size of column to show the detail. (b) The user drags this cursor towards the left and the information, which was previously hidden, is uncovered.

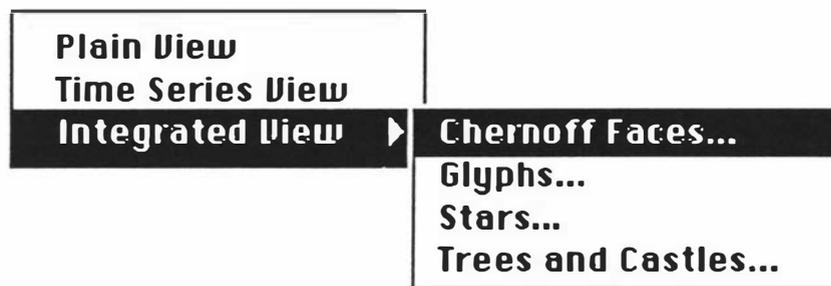


View Control

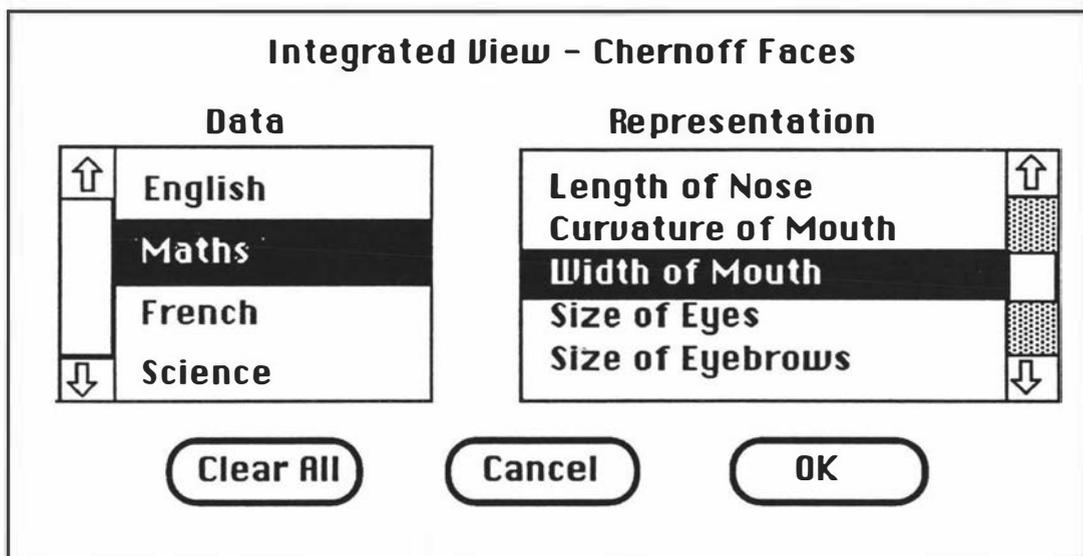
Multi-dimensional data sets can be organised, represented and presented on the computer screen in a variety of ways and they are constrained by the 2-dimensional display surface. The view control allows the user to select a view of a multi-dimensional data set. Three views of the data are available: a plain view, a time-series view and an integrated view, upon activation of the mouse on this button (Figure 6.8a). The underlying data are organised in different ways to facilitate decision making. It should be stressed that the view control may be used in conjunction with the representation control to yield the optimal result for a particular task.

The plain view selection presents the data set as it is stored in the spreadsheets. Tufte (1983, p.27) suggests that the time-series plot is the most frequently used form of graphic design. In a random sample of 4000 graphics drawn from 15 of the world's new papers and magazines published from 1974-1980, Tufte found more than 75% were time-series. A time-series view of the data is provided for this important kind of data set to enable the user to carry out tasks such as trend analysis and data comparison.

An integrated view is particularly useful for multi-dimensional data as it allows the user to take a global view of the data to support decision making tasks. Various representations of the multi-dimensional data, such as Chernoff faces, stars and glyphs, are available for different types of decision making tasks. Figure 6.8b shows how the user can select various facial attributes to represent the multi-dimensional data.



(a)



(b)

Figure 6.8 The menu and dialogue box for specifying an integrated view. (a) The menu for selecting an integrated view of data. (b) The user can select various facial attributes to represent the data.



Filter Filter Control

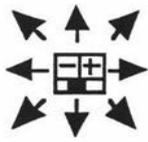
This control allows data within a selected range as specified by the user to be identified quickly. This feature of the InfoLens is particularly useful in situations where the user may wish to examine data which satisfy certain criteria. When this icon is activated, the system prompts a dialogue box to enable the user to select the attributes and their ranges.

Data		Selected Range	
1	English	From: <input type="text" value="50"/>	To: <input type="text"/>
2	Maths	From: <input type="text" value="50"/>	To: <input type="text"/>
3	French	From: <input type="text" value="50"/>	To: <input type="text"/>
4	Science	From: <input type="text"/>	To: <input type="text"/>

Filter Expression:

Figure 6.9 A dialogue box for specifying the Lens Filter

Figure 6.9 shows the arrangement of this dialogue box. In this example, the user selects the students' subject scores in English, Maths and French which have a value of 50 or higher. The user can then use the mouse and the selection buttons to create a logical filter expression; in this case, the user is interested in examining the marks where a student passes both English and French but fails Maths.



Navigation controls

In the context of the lens metaphor, the navigation controls are analogous to the panning action of the lens over the information space. The scroll bars in the display area support this operation and the navigation controls provide a finer manipulation of the panning action in a number of ways. First, whilst the scroll bar supports four directions of movement, the navigation control provides eight possible directions of movement. Second, the panning action may be activated continuously by depressing the mouse button when the cursor is placed on one of the eight arrows in the navigation controls. The use of morphing algorithm would allow the user to pan across the information space fluidly as if he or she was holding a magnifying lens. This feature is desirable as empirical findings in Chapter 3 suggest that a user performs better with a scrolling interface than with a point and click interface. Third, the gain control of the scroll movement may be adjusted. This is achieved by progressively activating the '-' or '+' button in navigation controls using a mouse, with a corresponding decrease or increase in the gain control of the scroll movement. When one extreme of the setting is reached, the inactive button is dimmed, thus allowing the setting to be changed in the opposite direction. The bottom scroll bar mechanism allows the user to adjust the scrolling speed quickly.

In addition to the above navigation controls, the user may also move the central focus area from one point of the information space to another quickly using a point and click action, directly manipulating on the display area.



Container

As the tasks of interpreting an item and relating it to other items within various locations in the information space are frequently executed, special facilities to support these tasks would be of great practical value to the user. The container is a temporary storage area which enables a set of selected items to be compared later. The user may put an item of interest into the container by dragging it from the display area; an array of data may also be deposited in a similar way by marking them in the display area first. To provide immediate and useful visual feedback to the user, a marker is generated automatically in the container in the position relative to the entire information space. The size of the markers is proportional to the number of items selected. An item may be

removed by dragging it out of the container; the entire column or row may be selected and manipulated in the same way. Items in the container may be examined and compared by double clicking the container area; the Bifocal view of the entire data base will be replaced by the selected items in the container.

August, 1994

Company Name	Price Aus \$	P/E ratio	NTA Aus \$	Div Yield %	Vol Current Month	Vol Average
BHP	17.98	17.78	6.47	2.45	53377	68544
New Corp	8.36	16.38	6.05	0.36	50528	60516
Nat Aust Bank	10.96	9.67	5.51	5.57	47100	55036
CRA	17.80	13.81	7.19	3.93	16263	21654
BTR Nylex	2.90	18.42	1.27	3.79	50986	54849
Westpac	4.46	15.37	3.38	3.14	54847	68744
Fletcher	3.07	11.82	1.47	3.20	10937	10837
WMC	7.21	83.60	2.92	1.53	62822	67851
Com Bank Aust	7.77	13.01	5.58	5.92	13159	17177
Telecom NZ	3.70	17.23	0.93	5.33	629	344
ANZ Bank	4.02	10.97	3.43	5.22	72277	67892
AMCOR	9.04	19.26	3.48	3.54	14070	19054
Coles Myer	4.24	13.94	2.44	4.60	41822	37273
Carter Holt	3.00	24.37	1.55	2.21	2211	4392
MIM	2.88	n/c	1.87	1.74	85866	113030
Pac Dunlop	4.31	15.63	1.34	4.87	37909	43826
CSR	4.80	14.38	3.31	5.21	35556	37918
Lend Lease	16.26	16.42	9.81	4.74	4755	6723
Boral	3.34	24.63	2.05	5.95	37910	35780
Fosters	1.06	9.26	0.55	5.66	99999	113391
CC Amatil	8.65	34.00	2.87	2.08	4262	4772
ICI Aust	10.70	20.15	3.91	2.52	6823	10538
Woodside Pet	4.60	29.79	1.64	1.74	21482	19335
Brierley	1.01	10.80	1.07	7.24	6823	10538
Woolworths	2.89	n/a	n/a	4.15	29453	35983
Brambles	13.04	n/c	5.39	4.60	8237	10264
Comalco	5.13	36.40	2	1.17	11710	10645
Pioneer Int	2.87	17.40	1.86	5.23	30559	41634
Mayne Nick.	7.92	51.19	2.67	3.91	10758	14935
Lion Nathan	2.58	23.00	n/c	4.57	1919	2428

Table 6.1 An excerpt from a financial database. The top 30 Australian companies shown in descending order of market capitalisation

6.3.2 InfoLens in action

The operational aspects of the interface controls of the InfoLens have been discussed in detail in the previous subsection. In this subsection, the display capability of the InfoLens is illustrated to show how it can be used to support the user to perform various tasks, including decision making. These illustrations provide some of the snapshots of the InfoLens showing how it works with different types of data. An inherently graphical data system, which is typified by the London Underground Map, is considered first. Train departure information is embedded in the station symbols of the electronic map. For simple information retrieval tasks, the user locates the station of interest by scrolling the Bifocal Display of the InfoLens until the station is displayed in the in-focus region. A double click on the station symbol reviews the train departure information; the visual display will be similar to that shown in Figure 4.16. The InfoLens is particularly well suited to this type of application for geographical information systems. Maps with an oblong shape may be appropriately presented using a one-dimensional Bifocal Display.

To demonstrate how the InfoLens can be applied to an inherently non-graphical data set, a spreadsheet containing financial information about the top 100 companies (by market capitalisation) listed on the Australian Stock Exchange is used. The financial information of these companies in the spreadsheet includes monthly volume traded, net tangible asset per share and dividend yield over a period of 12 months. Table 6.1 shows an excerpt from this database taken from the Personal Investment magazine. The database contains essential information which enables the financial analyst as well as any investor to compare any of these stocks. Often, investment decisions have to be made in a very short time frame and it is important that the user of this database can extract and interpret the required information as quickly as possible.

Figure 6.10 shows a typical view of the InfoLens when the spreadsheet is first loaded. The data are displayed according to the way they are stored in the spreadsheet. The InfoLens uses the Bifocal Display technique and presents an area of interest in detail in the centre and at the same time provides a global, albeit distorted, view of the entire information space. The user may manipulate the interface controls directly on this space. Figure 6.11 shows the view after the user has 'opened up' the information space under the heading September 1994, creating a multi-focus view. As this space is unfolded, the system calculates the space requirement to accommodate the additional information and updates the display; in this example, the column widths of the month strips have been reduced in size accordingly.

Name	Jan	Feb	Mar	Apr	May	Jun	July, 1994					Aug	Sep	Oct	Nov	Dec		
	1994	1994	1994	1994	1994	1994	Price	P/E	NTA	Yield	Volume	Avg Vol	1994	1994	1994	1994	1994	
							\$		\$	%	,000	,000						
Goodman F.							1.39	13.88	0.92	8.59	50,107	62,787						
Homestake							1.83	39.53	0.24	0	5,169	10,290						
Howard S.							6.40	19.84	2.50	4.46	10,885	6,708						
ICI Aust							10.70	20.15	3.91	2.52	4,291	2,995						
Lend Lease							16.50	16.66	9.81	4.74	6,711	7,131						
Lion Nathan							3.00	26.74	n/c	4.57	4,105	2,868						
Mayne N.							8.81	56.95	2.67	3.91	15,283	15,962						
MIM							3.13	n/c	1.87	1.74	99,999	121,018						
Nat Aust Bk							11.82	10.44	5.51	5.57	57,808	51,698						
New Corp							9.03	17.69	6.05	0.36	67,638	62,028						

Figure 6.10 A typical view of a financial database through the InfoLens

Name	1	2	3	4	5	6	July, 94					8	September, 94		10	11	12	
	94	94	94	94	94	94	Price	P/E	NTA	Yield	Volume	Avg Vol	94	Price	P/E	94	94	94
							\$		\$	%	,000	,000		\$				
Goodman F.							1.39	13.88	0.92	8.59	50,107	62,787		1.43	12.78			
Homestake							1.83	39.53	0.24	0	5,169	10,290		1.79	39.96			
Howard S.							6.40	19.84	2.50	4.46	10,885	6,708		6.38	19.10			
ICI Aust							10.70	20.15	3.91	2.52	4,291	2,995		11.10	20.15			
Lend Lease							16.50	16.66	9.81	4.74	6,711	7,131		16.70	16.42			
Lion Nathan							3.00	26.74	n/c	4.57	4,105	2,868		2.72	23.00			
Mayne N.							8.81	56.95	2.67	3.91	15,283	15,962		7.77	51.19			
MIM							3.13	n/c	1.87	1.74	99,999	121,018		3.00	n/c			
Nat Aust Bk							11.82	10.44	5.51	5.57	57,808	51,698		11.16	9.67			
New Corp							9.03	17.69	6.05	0.36	67,638	62,028		8.70	16.38			

Figure 6.11 A multi-focus view of the same database

The InfoLens allows various views to be selected via the view control button. For tasks which involve the detection of trends in time-series data, it is useful if the data may be presented to the user in a different format. Figure 6.12 shows the rearrangement of the data in the spreadsheet and a multi-focus view with the price and volume information presented as separate bar graphs as a result of selecting a time-series view. It should be pointed out that as the share prices of different stocks may vary significantly, it is more meaningful for the analyst to compare the trends of the price and volume movement of these stocks. The bar heights shown in Figure 6.12 have been appropriately scaled to the range of values related to the individual stock. Other representations of the time-series data are provided through the use of the representation control/indicator button.

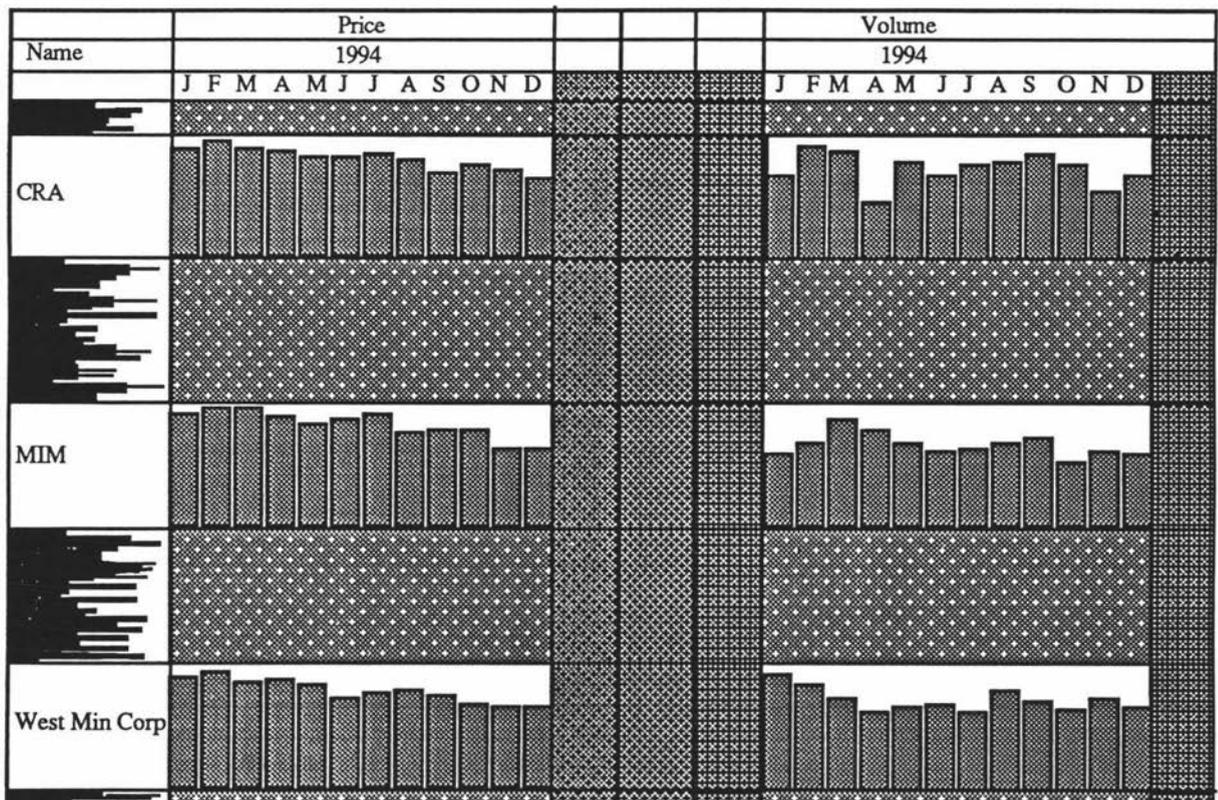


Figure 6.12 A multi-focus view showing time-series data

Multi-dimensional data may be shown as an integrated object to facilitate tasks such as cluster analyses. Chernoff (1973) suggests the use of cartoon faces for representing multi-dimensional data as they allow the user to detect time points where a multi-variate stochastic process changed character. Flury and Riedwyl (1981) extend

Chernoff's idea and use asymmetrical and more human-like faces for data representation. Other novel techniques, using glyphs, star, trees and castles, and integrated icons, have also been developed by various researchers to represent multi-dimensional data. Figure 6.13 shows a multi-dimensional view of three mining stocks over a six month period; the six facial features used to represent the multi-dimensional data are:

- width of head - average volume
- height of head - current month volume
- width of eye - price
- length of eyebrow - net tangible asset
- P/E ratio - length of nose
- dividend yield - curvature of mouth

Using a dialogue box similar to that shown in Figure 6.8b, the user may change or reassign these facial features for the data.

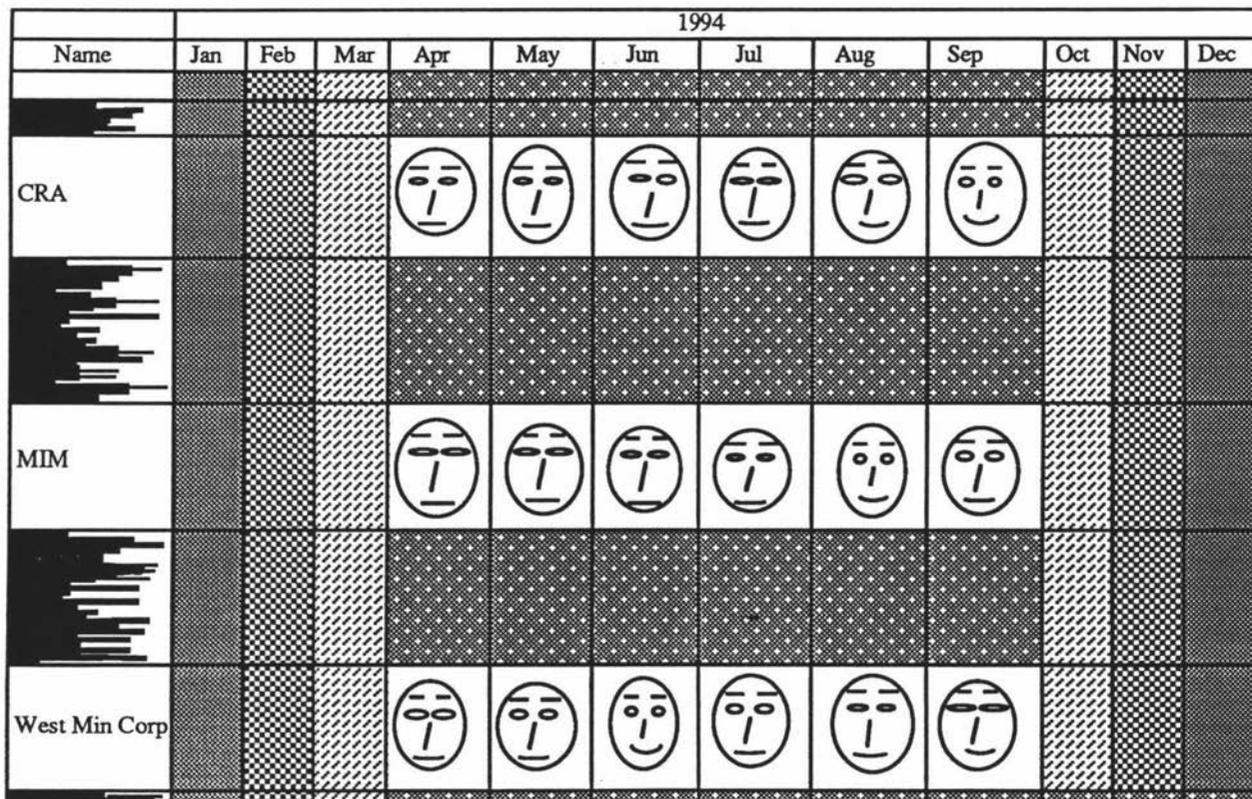
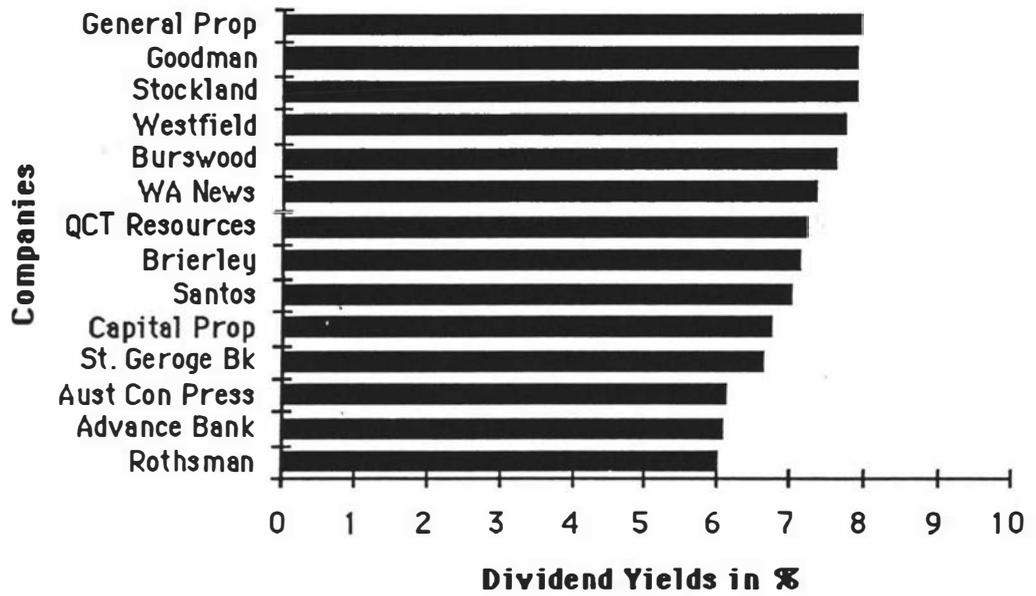
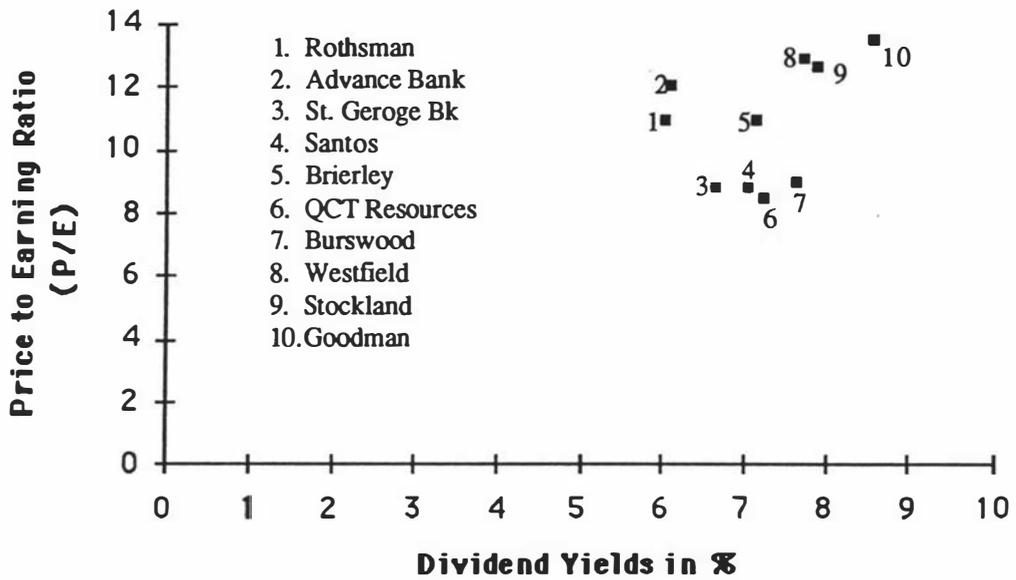


Figure 6.13 An integrated view of the multi-dimensional data using Chernoff faces



(a)



(b)

Figure 6.16 A presentation and comparison of the data stored in the container: (a) stocks with a dividend yield of 6% or higher; (b) stocks with a dividend yield of 6% or higher and a price to earning ratio of 14 or lower.

The lens filter allows the user to highlight the relevant data to facilitate further investigation. Figure 6.14 shows the display on the InfoLens where the user selected to view stocks with a dividend yield of 6% or higher. Data which do not satisfy this conditions are de-emphasised. Figure 6.15 shows how logical operations may be applied when selecting the lens filter; stocks with a dividend yield of 6% or higher *and* a price-to-earning ratio of 14 or lower are highlighted. Stocks which satisfy the specified conditions are highlighted in the main display area as well as in the container. If the user wishes to compare these stocks further, they will be conveniently presented on the display by double clicking on the container. Figure 6.16 shows a comparison of the stocks which satisfy these conditions. Additional items, or groups of items, may be selected and dragged into the container using a mouse for further examination in a similar way.

6.4 Implementation Issues

The InfoLens is intended to be a generalised tool for the visualisation of large data sets. At start-up time the system loads the data from a database along with a number of supporting graphical data files. For example, in the London Underground timetable system, the system loads the timetable information from a database together with various graphics files containing the bitmaps for the construction of a Bifocal Display of the London Underground map. The change of the window size or the magnification factor in the in-focus region (adjusting the distance between the lens and the viewer) will have direct implications for the magnification factors in other regions of the Bifocal Display. With the Bifocal Display, the system will require four additional bitmaps to support every set of these system parameters; the number of these files the system has to keep track of could be quite large. Further, these bitmap files are invariably large and if they are to be loaded into memory at start-up time, a lot of the system's primary memory resources will be required. In addition, a sophisticated memory management system will generally be necessary to control the activities which take place within the system. The use of secondary storage elements to support the system may be viable if the system response time is not significantly downgraded due to a page fault in the course of a memory swapping operation.

The memory resources and computational power of any real time interactive system are the most valuable commodities available to the system designers. Based on the relevant design criteria, the designer makes compromises between these commodities, aiming to achieve optimal overall system performance. In the case of the implementation of the InfoLens, an obvious way to reduce system complexity would be

to cut down the number of these graphics files required to support the system. Unfortunately, this would have the undesirable effect of restricting the range and scope of the 'lens'. If the system is computationally powerful, one effective solution would be to generate the various sets of bitmaps for the Bifocal Display on the fly. Depending on the platform for implementation, dedicated hardware or efficient software modules may be used to support this. Using this scheme, a significantly reduced number of these bitmap files will be required to be downloaded at system start up time.

In the course of interaction with the InfoLens, the user will invariably adjust the 'lens' to navigate around the information space. This can be supported by using animation and morphing techniques (Foley, van Dam, Feiner & Hughes, 1990; Mason, 1994; Vince, 1992) to create a more dynamic interface, allowing the user to browse naturally. A sense of control over the 'lens' is thus created and the system provides a rich and natural style of direct manipulation. The effectiveness of this dynamic interface relies very much on the computational power of the system. The generation of animated sequences on the display in real time often places a huge burden on system resources. A performance enhancement technique, known as greeking (Robertson & Mackinlay, 1993), can be used to reduce the amount of computation required during the generation of animated sequences. The essence of this approach is to reduce the resolution of the display in the out-of-focus regions, thus lessening the burden on the system resources. Indeed, greeking may also be applied to the display at all times if system resources are limited or if a less detailed view may be tolerated in the out-of-focus region.

Colour is an essential ingredient of a display. There is evidence to suggest that colour supports efficient preattentive visual processes (Nothdurft, 1992). Experimental studies have also shown that observers can more rapidly pick out symbols defined by colours than symbols defined by shapes (Davidoff, 1987; Treisman & Gelade, 1980). Furthermore, colour searches are found to be parallel and search speed is unaffected by the density of irrelevant elements. However, Smith, Dunn, Kirsner & Randell (1994) suggest that "designers should not assume that colour is always desirable, but rather its full perceptual and cognitive implications need to be understood and considered in relation to the demands of each task and therefore each display".

Whilst all the illustrations of the InfoLens in the previous section have been presented in black and white for ease of their production, colour should be used selectively in the implementation of the InfoLens.

Increasingly, the object-oriented approach has been adopted in the design and implementation of user interfaces and complex user interface management systems (Linton, Vlissides & Calder, 1989; Myers, Giuse, Dannenberg, Zanden, Kosbie, Pervin, Mickish & Marchal, 1990; Tyler, Schlossberg, Gargan Jr., Cook, & Sullivan,

1991; Bass & Coutaz, 1991; Zamer & Chew, 1992). This approach utilises a uniform underlying representation from object-oriented analysis (OOA) to object-oriented design (OOD) and then to object-oriented programming (OOP): the analysis stage is directly mapped to the design stage and the design stage mapped directly to the implementation stage. It also provides a stable framework for understandability, re-usability and extendibility. This continuum of representation throughout the development process results in no major difference in analysis and design notation, no more "transiting" into design and no waterfalls (Coad, 1991). This optimum route from OOA to OOD to OOP is recognised as one of the great strengths of the object-oriented approach (Bailin, 1989).

Whilst the concepts of inheritance and encapsulation are the two driving principles of the object-oriented approach, the design and implementation of the InfoLens are well suited to this approach. First, as far as the interface objects go, their functionalities and behaviours are well defined. Second, reusability of code allows easy extension of the interface in the future. Third, the hierarchical structure of the bitmap files required to support the Bifocal Display of the information space provide a natural mapping for implementation.

6.5 Review

This chapter has examined the key concepts of the lens metaphor and discussed the basic operations of a magnifying/photographic lens. This lens metaphor has been extended to show how it can be applied to visualising large data sets in the design of a visualisation tool, the InfoLens.

The user interface of the InfoLens has been designed to conveniently map the functionalities of a magnifying/photographic lens to those used to visualise a large data space. An iterative design of the InfoLens has been proposed and implementation issues relevant to the system performance highlighted.

Chapter 7

Conclusions and Further Work

"Data is not information is not knowledge is not wisdom."

Anon.

This final chapter summarises the essence of this thesis and identifies future research work to be conducted to enable a better understanding of issues related to the visualisation of large information spaces. Section 7.1 provides a summary of the chronological development of this piece of research and Section 7.2 reviews critically the InfoLens, a visualisation tool based upon the theoretical frameworks developed. Section 7.3 highlights the contributions of this research which address the large-world-small-screen problem. The final section (Section 7.4) identifies various areas of future research work which should be pursued to advance our knowledge of data visualisation.

7.1 Summary of the Thesis

The principal objectives of this research, as pointed out in Chapter 1, have been to study and characterise visualisation techniques for large databases and to propose a design of a general visualisation tool for the presentation and navigation of large information spaces on a small display surface. In the course of this research, there were three distinct phases. The first phase consisted of a detailed study of the Bifocal Display

and other presentation techniques. The second phase focused on the development of theoretical frameworks to assist with understanding these techniques and the visualisation process. The final stage entailed a detailed design of the general visualisation tool which builds upon these theoretical frameworks.

The Bifocal Display was selected for the initial investigation because of the simplicity of this approach in providing the user with a global view and at the same time, supporting local details; the simultaneous display of these two views is essential in facilitating adequate navigation in large information spaces. The original Bifocal Display was based on the application of demagnification in one dimension at a time; as such, this technique was restricted in its applications. To overcome this limitation, this research extended the Bifocal Display to a two-dimensional form, as illustrated in the implementation of the London Underground map and the Melbourne Metropolitan Railway map. The extended form broadened the applicability of this technique to display information structures with a two-dimensional hierarchy, such as tables and databases.

An experimental study was then conducted to compare the effectiveness of the Bifocal Display with other interfaces based on the London Underground map. The qualitative and quantitative data collected suggests the Bifocal Display is an effective approach in presenting a large information space on a small display screen.

Over the years, a variety of novel and sophisticated presentation techniques involving the application of distortion to different areas of a display have been proposed by various researchers. The development of these interfaces has brought with it numerous terminologies and considerable mystique surrounding these interfaces which have been brought about by their seemingly different appearances. Consequently, there is a great need to develop a taxonomy to clarify the confusion of terminologies and to unravel the mystique of ever increasing new presentation techniques confronting graphical user interface designers. Further, a well defined classification of these techniques will help to make the comparison and generalisation of empirical results of experiments using these techniques a much easier task. A taxonomy based on the underlying magnification function of the interface has been put forward; interfaces may be classified into those with a continuous magnification function and those with a non-continuous magnification function. A conceptual model of these distortion-oriented presentation techniques has also been proposed to show their roots and origins and account for their behaviour and limitations.

Whilst the taxonomy and conceptual model of distortion-oriented presentation techniques have formed a firm foundation for understanding these types of interfaces, they do not provide a useful framework for the selection of a presentation technique for a particular application. Indeed, the choice of a technique for a particular application is

often very subjective and there is a great need to develop an analytical framework to facilitate a more objective assessment of presentation techniques for large data sets. The proposed E³ framework is based on the representation and presentation of data and its underlying concept mirrors closely to the information flow which takes place from the data to the viewer during the visualisation process. Three areas of metrication are proposed in this model based on the efficiency, expressiveness and effectiveness of an interface.

The final phase of this research is built upon the new knowledge and understanding of distortion-oriented presentation techniques. It involves the development of a visualisation tool for large spreadsheets and databases. The InfoLens, which is based on the Bifocal Display and the Lens Metaphor, has been designed to demonstrate the effectiveness of the Bifocal Display in presenting large data sets. This visualisation tool aims to support various tasks typically performed by users of spreadsheets and databases, ranging from data exploration to decision making tasks.

7.2 Review of the InfoLens

As pointed out in the previous subsections, the design of InfoLens has been based upon the theoretical frameworks developed in this research. The InfoLens is designed to facilitate user interaction with large data sets, particularly those with an inherent spatial relationship and those which can be abstracted in graphical form, by enabling these data sets to be viewed in a number of ways so that the user can perform the task at hand effectively. The design of InfoLens is task-oriented, with due consideration to the three key tasks: locating, interpreting and relating, to be carried out by the user.

The Bifocal Display, the usability of which has been demonstrated, is the presentation strategy underpinning the design of InfoLens. Further, the Lens Metaphor has been proposed to illustrate the underlying concept and operation of the InfoLens. For example, controls are available to adjust the size of the viewport, to navigate around the workspace, as well as to change the focus (or clarity) of the data presented. The ease of operation of the InfoLens, coupled with an effective interface, is an important feature of a usable visualisation tool. On the one hand, appropriate system response time is paramount to the usability of InfoLens; on the other hand, the system should be readily implementable using existing technology.

7.3 Original Contributions

In the course of this research, a number of original contributions have been made towards the understanding of presentation techniques for large information spaces. These contributions may be summarised as follows:

- The one-dimensional Bifocal Display originally proposed by Spence & Apperley has been extended to a two-dimensional form and illustrated using the implementation of the London Underground map and the Melbourne Metropolitan Railway map. This extension has demonstrated that large information spaces with a spatial relationship may be presented effectively on a relatively small display surface.
- A further extension of the two-dimensional Bifocal Display technique has been presented. This concept allows complex presentation techniques, which typically require a huge amount of the system's computational time, to be approximated by a number of stepwise magnification factors in the magnification function. Using this approach, bitmaps of various magnification levels may be pre-generated and stored in memory. Consequently, an effective scrolling interface may be supported without the need of a high-power computing machine.
- An evaluation of various presentation techniques using the implementations of the London Underground map has been performed to ascertain the effectiveness of the Bifocal Display in comparison with other techniques.
- A taxonomy of distortion-oriented presentation techniques has been proposed to clarify the terminologies and to unravel the mystique of ever increasing new presentation techniques confronting graphical user interface designers.
- A better understanding of distortion-oriented presentation techniques has been gained from the conceptual model presented. This conceptual model shows the roots and origins of distortion-oriented presentation techniques and accounts for their behaviour and limitations.
- The E^3 model described in this thesis has provided a theoretical framework for the metrication of graphical presentation techniques for large data sets. This framework enables the interface designer to select a presentation technique for a particular application more objectively.
- A design of a general visualisation tool, the InfoLens, based upon the Bifocal Display and various theoretical frameworks described in this research, has been discussed. InfoLens enables large spreadsheets and databases to be presented

on a relatively small display screen to support a variety of tasks which are typically performed by users.

7.4 Future Research Work

The work described in this thesis encompasses a wide span of domains related to data visualisation, ranging from usability studies, HCI theory and visualisation techniques to interface design and implementation issues. There is, therefore, a variety of work which could be pursued to further advance the knowledge and understanding of issues associated with the problems of visualising large information spaces over the small display screen. The following subsections describe some of the major areas of research which could stem from the current work.

Implementation and Evaluation of the InfoLens

The iterative design of the InfoLens described in the previous chapter has provided the necessary groundwork for its full implementation. This implementation would then facilitate a thorough evaluation of the system using a variety of spreadsheets, tables and databases with varying attributes, such as size, data types and data structures. User performance on various tasks may also be compared with other display formats and systems, such as the more conventional tables and displays of databases on the computer.

The functionality of the InfoLens may also be integrated as a key component of a database system, supporting a comprehensive range of operations. At a higher level, the database system establishes a permanent linkage with various files with graphical data to support the InfoLens. At a lower level, data, as they are entered and updated, would be automatically converted in various graphical formats to enable the user to undertake the task at hand; in this context, the user could be the viewer of the data, the administrator or the data entry operator.

Comparison and Evaluation of Distortion-Oriented Presentation Techniques

The underlying difficulty in the selection of distortion-oriented presentation techniques for a particular application is the apparent visual differences between these types of displays. Whilst the taxonomy and conceptual model of distortion-oriented presentation techniques proposed in this thesis have enriched our understanding of these approaches in presenting large information spaces, there is a great need to gather a body

of empirical data to compare the strengths and weaknesses of these techniques. This would help to make the selection process for an appropriate presentation technique an easier task. It is important to emphasise that in the comparison of these presentation techniques, system parameters should be carefully chosen so that the magnification factors in the in-focus and out-of-focus regions are as closely matched as possible. In order that a richer picture of the evaluation can be gained, a multi-dimensional evaluation approach (Burger & Apperley, 1991) is recommended. The empirical knowledge base so generated would help to strengthen the metrication framework proposed and help identify specific application domains for these techniques.

A deeper understanding of the user interaction with these types of interfaces can also be gained by developing detailed cognitive models to account for and predict user behaviour and performance. The cognitive model on user interaction with map-based user interfaces described in this thesis has identified three key constituents: states, processes and resources. Further observational studies on other types of graphical user interfaces would help to extend this model in a number of ways. First, the model could be extended to cover a wider range of graphical user interfaces. Second, the model could be strengthened to account for the full range of interface experience, from original goal formation to system state evaluation. Third, a more elaborate model could facilitate accurate prediction of user performance of a variety of tasks using these graphical user interfaces.

Extending the E³ Framework

The E³ metrication model described in this thesis has provided a useful framework for the user interface designer to make an objective assessment and comparison of various presentation techniques. This framework suggests the information flow starts from the representation of the data to the user in the performance of a particular task. A formal analysis of this information flow using established information theory would help to identify the existence of any bottlenecks which could potentially impede user performance. Research into the amount of textual information to be displayed on the screen suggests there is an optimum information density (Danchak, 1976; NASA 1980). A formal analysis would help to identify an optimal value for the presentation of graphical data.

The robustness and usefulness of the E³ metrication model currently relies much on empirical data which provides the knowledge base for *expressiveness* and *effectiveness*. The study of the former is typically carried out by psycho-physicists; the latter by user interface evaluators. Recent work on the development of a cognitive model

for the understanding graphical perception (Lohse, 1993) would also contribute to the formation of a more robust and versatile metrication model.

Visual Illusion in Data Visualisation

Recent advances in computer graphics technologies have contributed to the development and applications of many sophisticated data visualisation and interaction techniques. These approaches enable complex multi-dimension data to be presented on the display screen and, increasingly, 3D visualisation is common in the presentation of large data sets. Whilst these techniques provide a powerful means of representing and presenting complex data, it should be emphasised that the main aim of data visualisation is data comprehension, enabling the viewer to perform the task at hand.

These visualisation techniques are potentially powerful, as they allow patterns which are inherent in the data set, but which would otherwise remain obscured, to unveil themselves. However, misuse of these techniques may impede data comprehension, and may even lead to misinterpretation of the data. Visual illusions have been a well researched topic in psychology over the past one hundred years. However, their effects on data visualisation in computer applications have been under-explored. Tufte (1983) describes the use of illusion in graphical presentations in terms of the lie factor. There is some research evidence to suggest that users perform less effectively with 3D graphics than conventional 2D graphs (Barfield & Robless, 1989; Carswell, Frankenberger & Berhard, 1991). Much further work is needed to develop a set of practical guidelines for user interface designers and practitioners to identify the potential pitfalls in data visualisation.

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Appendix A

An Experiment on Graphical User Interfaces for Topological Maps

Appendix A.1: Experiment 1 - General Information Sheet

Interacting with Map-Based Graphical User Interfaces

Thank you for participating in this study. The study involves trying to understand how people use a *travel information system* as might be found on any rail platform. We want to know if the computer will help you find the locations of stations and plan your route. Please don't feel inhibited, if you can't answer our questions it is probably because the computer isn't designed very well.

We would like you to do the tasks listed below. At the same time would you please **say out loud everything that you are thinking**. This is important and will help us understand what you are doing and why you are doing it.

The video camera will help us record what you do. This information will be treated in the strictest confidence.

Please feel free to ask questions during any part of the study.

Please start and continue until all of the tasks are complete.

Please play with the **Melbourne** train map which has been presented on the display screen. Get used to the speed with which the screen information is updated as you move the mouse. Note that this speed depends on the movement (the bigger the movement the longer it takes) and the direction (it is faster in the horizontal direction than the vertical direction). When you feel comfortable with the system move on to the next step. **Don't forget to think aloud throughout the study.**

Appendix A.2: Experiment 1 - Instruction Sheet

Instructions

Identify the following stations in the **London** Rail map shown and try to establish their relative positions on the map. Do not worry about the line names, identify them by their colours. Write down the line colours of the trains which pass through the stations, e.g. Green Park - Grey, Light blue and Dark blue. Note that the stations are all in the central zone of the map.

- | | | |
|----|---------------------------------|-------|
| a. | Green Park | _____ |
| b. | King's Cross St. Pancras | _____ |
| c. | Notting Hill Gate | _____ |
| d. | Embankment | _____ |
| e. | Oxford Circus | _____ |
| f. | Baker Street | _____ |

Paper Map

Perform tasks 1a,2a,3a,4a,5a from the task lists

Bifocal Display - Point and Shoot

Perform tasks 1b,2b,3b,4b,5b from the task lists

Bifocal Display - Scrolling

Perform tasks 1c,2c,3c,4c,5c from the task lists

Scrolling View

Perform tasks 1d,2d,3d,4d,5d from the task lists

Split Screen

Perform tasks 1e,2e,3e,4e,5e from the task lists

Appendix A.3: Experiment 1 - Task Lists

TASK LISTS

- 1a. You have to meet a friend at **Liverpool Street** station in **East** London. Find the station.
- 1b. You have to meet a friend at **Kentish Town** station in **North** London. Find the station.
- 1c. You have to meet a friend at **Clapham South** station in **South** London. Find the station.
- 1d. You have to meet a friend at **Ruislip Gardens** station in **West** London. Find the station.
- 1e. You have to meet a friend at **Wapping** station in **South East** London. Find the station.
- 2a. You have a business meeting at **Shepherd's Bush** station near **Notting Hill Gate** station. Find the station.
- 2b. You have a business meeting at **St James's Park** station near **Embankment** station. Find the station.
- 2c. You have a business meeting at **Finchley Road** station near **Baker Street** station. Find the station.
- 2d. You have a business meeting at **Caledonian Road** station near **King's Cross St Pancras** station. Find the station.
- 2e. You have a business meeting at **Hyde Park Corner** station near **Green Park** station. Find the station.
- 3a. You have to meet a friend at **Clapham South** station on the **black** line. Find the station.
- 3b. You have to meet a friend at **Liverpool Street** station on the **red** line. Find the station.
- 3c. You have a business meeting at **Shepherd's Bush** station on the **red** line. Find the station.
- 3d. You have a business meeting at **Baron's Court** station on the **dark blue** line. Find the station.
- 3e. You have a business meeting at **Kensal Green** station on the **brown** line. Find the station.
- 4a. You have to change from the **red** line to the **light blue** line. How many places can this be done.
- 4b. You have to change from the **light blue** line to the **green** line. How many places can this be done.
- 4c. You have to change from the **dark blue** line to the **light blue** line. How many places can this be done.
- 4d. You have to change from the **green** line to the **red** line. How many places can this be done.

-
- 4e. You have to change from the **yellow** line to the **black** line. How many places can this be done.
- 5a. You have to meet a friend at **Liverpool Street** station in **East London**. Find the station. How would you get from there to **East Acton** Station.
- 5b. You have to meet a friend at **Kentish Town** station in **North London**. Find the station. How would you get from there to **Leytonstone** station.
- 5c. You have to meet a friend at **Clapham South** station in **South London**. Find the station. How would you get from there to **Embankment** station.
- 5d. You have to meet a friend at **Shepherd's Bush** station in **West London**. Find the station. How would you get from there to **Lambeth North** station.
- 5e. You have to meet a friend at **Wapping** station in **South East London**. Find the station. How would you get from there to **West Hampstead** station.

Appendix A.4: Experiment 1 - The Questionnaire**Questionnaire**

1. The statement which best describes your experience with the operation of a computer is,
 - a. You have very little experience with computers
 - b. You can operate a computer with minimal assistance
 - c. You are confident in operating a computer
 - d. You have a good knowledge with computers and you use a computer on a regular basis

2. Before participating in this experiment, you
 - a. had never seen the London Underground map before
 - b. had very limited knowledge of the station names on the map and their locations.
 - c. were familiar with at least ten stations and their locations and had a working knowledge of the London Underground map.
 - d. had a good knowledge of the London Underground map

3. Rate the following interfaces in terms of your personal preference. (1 = very poor, 6 = very good)

Paper Map	1 2 3 4 5 6
Bifocal Display - Point and Shoot	1 2 3 4 5 6
Bifocal Display - Scrolling	1 2 3 4 5 6
Scrolling View - Scrolling	1 2 3 4 5 6
Split Screen - Scrolling	1 2 3 4 5 6

Date: _____

Time: _____

Name (Optional):

Appendix A.5: Experiment 1 - Quantitative Data

Table A.I is a summary of subjects' ratings of the various interfaces tested. 1 denotes very poor and 6 very good. The number in 14 points bold signifies the first interface used by the subject, for example, the test sequence of Subject No. 2 is: Split Screen, Wall map, Bifocal - P & S, Bifocal, Scrolling View.

Subject No	Wall Map	Bifocal - P&S	Bifocal	Scrolling View	Split Screen
1	5	6	4	4	5
2	2	4	4	2	5
3	5	5	3	4	1
4	6	2	4	5	5
5	6	6	2	4	1
6	5	5	4	4	5
7	5	5	4	4	5
8	5	5	6	4	2
9	4	5	6	5	4
10	6	6	4	5	3
11	4	6	4	4	1
12	3	4	5	6	6
13	6	1	2	5	3
Total	62	60	52	56	46

Table A.1

Table A.II shows additional information related to subjects' computer competency and prior knowledge of the London Underground map. The figures in Table I of subjects' ratings of the interfaces are also translated in preference order in Table II.

Subject ID No.	Computer + Competency	Map ^{''} Knowledge	Map Interface Preference (from highest to lowest) [*]
1.	4	1	(1=2, 4,3, 5)
2.	4	2	(2, 1=5, 3=4)
3.	4	1	(5, 2=3, 1=4)
4.	3	2	(1, 4=5, 3, 2)
5.	2	1	(1=2, 4, 3, 5)
6.	3	1	(1=2=5, 3=4)
7.	1	1	(1=2=5, 3=4)
8.	4	1	(3, 1=2, 4, 5)
9.	4	1	(3, 2=4, 1=5)
10.	4	1	(3, 2=4, 1=5)
11.	1	1	(2, 1=3=4, 5)
12.	3	1	(4=5, 3,2,1)
13.	4	1	(1, 4, 5, 3, 2)

⁺ Scale ranges from 1 to 4, 1=Novice User 4=Expert User

^{''} Scale ranges from 1 to 4, 1= User has no prior knowledge of the London Underground Map
4= User has good knowledge of the London Underground Map

^{*} Map Interface No. 1 = Paper Wall Map
2 = Bifocal Display - point and shoot
3 = Bifocal Display - scrolling
4 = Scrolling View - scrolling
5 = Split Screen - scrolling

Table A.II A summary of the results from the questionnaire

Appendix A.6: Experiment 1 - Qualitative Data

Table A.III shows the background data of the thirteen subjects who undertook the experiment.

Subject ID No.	Instruction Sheet No	General Background
1.	A	(M) Australian, Student
2.	E	(M) Australian, Admin staff
3.	B	(M) Pakistani, Student
4.	D	(F) Malaysian, Admin staff
5.	C	(M) Australian, Admin staff
6.	B	(F) Hong Kong, Admin staff
7.	C	(M) Hong Kong, Student
8.	A	(M) Australian, Student
9.	D	(M) Indonesian, Student
10.	E	(F) Sri-Lankan, Student
11.	A	(F) Greek, Admin staff
12.	B	(F) Indonesian, Student
13.	C	(M) Indonesian, Student

Table A.III Subjects' Background Data

Appendix A.7: Experiment 1 - Sample Qualitative Data of Two Subjects:

Subject No. 5. Sheet C Comp User: 2 Map User: 1 (M) Australian, Admin staff Pref: (1=2, 4, 3, 5)

Introduction to the London Underground Wall Map:

King's Cross St. Pancras - The subject searched from west to east systematically in the central London area and located the station.

Notting Hill Gate - The subject searched from King's Cross St Pancras station and moved eastward. The subject then found the station.

Embankment - The subject searched from Notting Hill Gate station and followed each line in the central area. The subject then found the station.

Oxford Circus - The subject searched from Embankment station and gradually moved north. The subject found the station by searching a sector at a time.

Baker Street - The subject started from Oxford Circus station and moved westward gradually. The subject then found the station.

25 Tasks from the Task Lists:

- 1c The subject scrolled the bifocal window downward and located the station.
- 2c Starting from the NE of the map (the subject could not remember the location of Baker Street station) and working downward, the subject found Baker Street and Finchley Road stations.
- 3c The subject located the red line from the current bifocal window, and found the station by gradually scrolling westward.
- 4c The subject located the dark blue line from the current window. Following along the dark blue line and moving westward the subject located the intersection station.
- 5c The subject scrolled the bifocal window downwards and spotted Embankment station. The subject then scrolled it further downward, Clapham South station was found. The route was found by positioning the two stations inside a bifocal window.
- 1d The subject moved to the bottom left screen and searched on the display thoroughly. Ruislip Gardens station was then spotted at the top of the screen.
- 2d The subject moved the display eastward and found both stations very quickly
- 3d The dark blue line was located in the current screen. The subject followed it and located the station
- 4d The subject anchored on the green line and moved the display to the extreme right. The subject then followed the green line to confirm there was no other intersection station.
- 5d The subject moved the display to the East and quickly located Shepherd's Bush station. The subject assumed Lambeth North station was in the north and searched carefully an area at a time. Gradually moving toward the west the subject found the station. The two stations were then positioned on the same display and the route identified.
- 1e Gradually moving the highlighted window to the SE area in the bottom section of the screen the subject located Wapping station on the top screen.
- 2e The subject could not recall where Green Park station was and gradually moved the highlighted area towards the centre of map and located both stations

- 3e The subject concentrated on the bottom half screen and found the brown line. Moving the highlighted window on the brown line and searching in the upward direction, the subject located the station.
- 4e The subject concentrated on the bottom of the map and found the intersection station. The subject then slowly scrolled along the line to find out if there was any other intersection.
- 5e The subject located Wapping station as in 1e. Starting from top right of the map the subject switched between top and bottom screens and gradually moved westward to locate the station. The subject tried to locate the route on the bottom screen but was not sure. The subject then concentrated on the top screen and found the route.
- 1a The subject started from the far east and then moved westward to locate the station.
- 2a The subject could not recall the location of Notting Hill Gate station and browsed around the perimeter of the central area. The subject then searched up and down moving westward, and both stations were located
- 3a The subject started searching on the black line at the bottom of the wall map and found the station very quickly.
- 4a Starting from the NE area where the red line began, the subject followed along the red line and found the intersection
- 5a The subject located Liverpool Street station quickly. Starting from the east side of the map working westward, the subject searched thoroughly and found the station.
- 1b The subject started to search in the NW area of the wall map and worked eastward to locate the station.
- 2b The subject scrolled the bifocal window to the centre of the map. The subject then moved eastward and found both stations.
- 3b The subject started to search from the NE of the map along the red line. Moving downward the subject located Liverpool Street station.
- 4b The subject moved the bifocal window to a corner and located the intersection station.
- 5b The subject found the station as in 1b. Concentrating on an area at a time, the subject located the station while gradually moving northward from the south.

General Comments:

The subject searched a small area at a time very carefully and consistently throughout the experiment. and performed all tasks well The subject moved the bifocal window to one corner in order to locate the route between to stations. He was misguided by the station name Lambeth North.

Comments on Individual Interface:

- Bifocal - Scrolling* The subject moved the bifocal window to one corner to locate the station
- Big map - Scrolling* The subject used this interface effectively although he was misled by the station name Lambeth North.
- Split Screen - Scrolling* The subject used this interface very consistently switching between the two half screens,
- Wall Map* The subject was very effective and efficient with the wall map.
- Bifocal - Point and shoot* The subject moved the window to one corner to locate the route.

Subject no 7. Sheet C Comp User: 1 Map User: 1 (M) Hong Kong, Student Pref:
(1=2=5, 3=4)

Introduction to the London Underground Wall Map:

Green Park - The subject started to search from the central area of the wall map and found the station later.

King's Cross St. - The subject started to search from the central London area and mistook Hyde Park Corner station as King's Cross St. Pancras station. Then the subject expanded his search outwards and found the station.

Notting Hill Gate - The subject remembered the station from previous search and located the station very quickly.

Embankment - The subject searched up and down in the central London area. Gradually moving to the east the subject located the station.

Oxford Circus - The subject remembered the location of the station from previous search and located it immediately.

Baker Street - The subject searched up and down in the West London region. Gradually moving east and located the station.

25 Tasks from the Task Lists:

- 1c The subject moved the bifocal window to the bottom and located the station very quickly
- 2c The subject remembered Baker Street station from previous task and located it very quickly. Randomly scanning around Baker Street station in the currently bifocal window the subject located Finchley Road station.
- 3c The subject scrolled the window on the red line and gradually moved eastward to locate the station.
- 4c The subject scrolled the bifocal window to show one extreme end of the dark blue line. The subject then followed it and found the intersection.
- 5c The subject remembered the locations of Clapham South and Embankment stations from previous task and first located Clapham south quickly as in 1c. The subject then scrolled the bifocal window upwards to locate Embankment station. The subject found the route by positioning the two stations inside the bifocal window.
- 1d The subject moved the display area to the west and scanned from top to bottom to locate Ruislip Gardens station very quickly.
- 2d The subject remembered the location of King's Cross St Pancras station and found the station quickly. Caledonian Road was then located by gradually moving the display upwards.
- 3d The subject anchored on the dark blue line on the current display and searched along it. The subject missed the station the first time, he was trying to match the pronunciation with the station names on the map and later found it the second time.
- 4d The subject started from the extreme west of the green line and moved eastwards to locate the intersection with the red line.
- 5d The subject moved the display to the west side of the map. Scanning up and down the display the subject located the station. With Lambeth North station, the subject tried to match the station name by its first letter 'L'. Scanning top and bottom on the current screen systematically the subject located the station. The subject then centred the display so that two stations appeared on the same screen and determined the route.
- 1e The subject concentrated on the bottom window and was disoriented and confused with the east direction. The subject moved to the opposite direction and after a

- while, moved back to the South East. Concentrating on the top window the subject located Wapping station.
- 2e The subject concentrated on the current window and gradually moved the highlighted window toward the centre. Both stations were then found fairly quickly.
 - 3e The subject scrolled the highlighted window to one extreme of the brown line and gradually moved northward without referring to the bottom screen. The subject got confused with the optical mouse but quickly rectified the problem and moved on the brown line to locate the station.
 - 4e The subject concentrated on the lower screen to locate the yellow line and worked on the upper screen to locate the intersection station
 - 5e The subject got confused with the SW direction with SE (same problem as in 1e) and worked on the lower half screen to move window to SE and found Wapping station. The subject moved the windows upwards, and matching station names with the first letter 'W'. After a long search, the subject was frustrated and scanning rather randomly. A while later the station was located. The subject tried to locate the route from the bottom map but later gave up. The subject then concentrated on the top window to identify the route.
 - 1a The subject was not sure where east was and confirmed the direction with the experimenter. The subject then searched through the stations name starting with the letter 'L' up and down on the map. The station was located after a short while.
 - 2a The subject remembered Notting Hill Gate station from the previous task and located it quickly. Scanning the stations around it, the subject located Shepherd's Bush station quickly.
 - 3a Following along the black line at the bottom of the map, the subject missed the station the first time. Later he re-searched the bottom area and located the station. The subject commented that he was not sure of the spelling of the station name.
 - 4a The subject found the light blue line on the map and searched along it to locate the intersection with the red line.
 - 5a The subject remembered the location of Liverpool Street station from the previous task and located it very quickly. The route was also quickly identified.
 - 1b The subject quickly moved the bifocal window to the north and systematically matched the station names starting with the letter 'K' and found the station.
 - 2b The subject remembered Embankment station was in the central area and worked from the West. Moving slowly to the central area the subject located the station.
 - 3b The subject remembered the general location of Liverpool Street station was in the central area. The subject located the bifocal window in the right place and found the station.
 - 4b. The subject went to the extreme west of the green line and searched along the line. The subject then found the intersecting station.
 - 5b The subject remembered the general location of Kentish Town station and found it immediately. Systematically working from the North and gradually moving to the East the subject located Leytonstone station. The subject then identified the route without moving the bifocal window.

General Comments:

The subject had good short term memory and worked systematically in searching for stations. The 'search by first letter' strategy had been used. However the subject failed to find Clapham South station as the subject could not remember the spelling of the station name. The subject was disoriented by the split screen interface as the system did not respond as fast as the subject expected.

Comments on Individual Interface:

Bifocal - Scrolling The subject worked very effectively with this interface, and had no problems working on the distorted area to identify intersection stations and routes

Scrolling View - Scrolling The subject worked very effectively with this interface.

Split Screen - Scrolling Subject appeared to have coordination problem with the mouse and got disoriented. The system did not respond as quickly as the user expected.

Wall Map The subject worked very effectively with the wall map.

Bifocal - Point and shoot The subject gained confidence with this interface and determined the route and intersection station from the bifocal window very quickly.

Appendix A.8: Experiment 2 Quantitative Data

Subj. No	Bifocal Scrolling			Bifocal Point and Click			Split Screen			Simple Scrolling		
	Task 1	Task 2	Task 3	Task 1	Task 2	Task 3	Task 1	Task 2	Task 3	Task 1	Task 2	Task 3
1	36	20	20	150	36	48	133	50	67	150	26	16
2	35	30	27	34	54	37	58	118	42	87	45	100
3	65	47	25	88	25	66	133	49	5	141	58	13
4	43	49	28	150	49	54	104	50	21	14	35	73
5	33	51	33	102	94	74	101	33	52	8	51	20
6	111	17	35	150	66	42	6	29	51	134	38	47
7	109	51	28	107	72	150	136	54	34	150	35	19
8	4	22	25	27	64	43	7	28	69	150	32	3
9	6	100	70	29	129	47	39	150	64	7	70	22
10	127	34	34	150	44	144	150	63	55	31	103	46
11	61	83	11	19	5	54	9	71	150	150	75	17
12	17	30	27	150	91	27	150	41	35	96	19	29
13	101	42	21	98	48	14	150	52	84	70	146	27
14	150	37	39	37	24	90	33	27	63	115	31	20
15	18	15	38	150	36	84	38	23	51	92	25	30
16	134	18	25	46	12	8	39	21	50	150	25	26
17	13	17	26	58	26	29	78	30	17	113	17	17
18	150	36	32	76	28	32	57	4	40	123	29	29
19	107	79	19	2	19	21	3	33	6	10	13	13
20	31	25	19	25	116	53	10	101	9	9	135	16
21	30	19	13	80	94	97	59	113	34	80	23	27
22	42	26	18	24	126	38	82	42	7	42	22	22
23	5	27	21	68	24	34	73	40	19	116	20	8
24	19	74	41	88	76	61	150	42	31	78	41	5
25	37	23	20	65	18	25	17	18	37	100	11	12
26	50	108	30	64	43	50	150	10	19	104	47	30
27	41	54	9	21	8	9	150	4	32	43	57	58
28	66	14	35	36	94	42	89	48	44	69	19	11
29	71	19	19	25	124	12	47	27	27	68	49	11
30	51	20	20	74	27	4	114	84	77	150	150	12
31	25	126	18	152	6	4	150	20	25	40	37	26
32	68	15	15	25	5	6	89	16	13	59	102	12
33	3	13	18	150	32	34	146	26	10	8	27	68
34	88	123	5	150	29	34	77	41	13	127	36	58

All task completion times in seconds. Typical tasks of Tasks 1-3:

Task 1. Locate STONEBRIDGE PARK *station* on the screen..

Task 2. From the station you have just located, move in a *south-east* direction to locate KENNINGTON *station*.

Task 3. Now locate ELM PARK *station* which is on the *green* line.

Appendix B

Mathematical Derivation of Transformation and Magnification Functions

This section presents the mathematical derivation of the transformation and magnification functions for various distortion-oriented presentation techniques discussed in this paper. The transformation function of a distortion-oriented technique defines the way in which a point in the original object image is transformed to the distorted target image, and the magnification function describes the degree of distortion which has been applied to a particular point of interest. Mathematically these two functions are related; the magnification function is the first derivative of the transformation function.

Due to the symmetrical nature of two these functions, only the positive horizontal x dimension of the object image has been used for their derivation. For points on the negative horizontal axis, the following relationships apply:

$$\text{Transformation Functions} \quad T(-a) = -T(a)$$

$$\text{Magnification Functions} \quad M(-a) = M(a)$$

where a has a positive value.

Table B.I shows the variables and notations which have been used throughout this section.

Symbol	Meaning
A	One of the two constants used in Polyfocal Projection
a	The boundary point between two regions of the object image in Bifocal Display and Perspective Wall
b	The boundary point between two regions of the target image in Bifocal Display and Perspective Wall
C	One of the two constants used in Polyfocal Projection
d	Distortion factor used in Fisheye View
k	Equivalent to $\frac{(1-b)}{(1-a)}$, and used in the derivation of the magnification function of Perspective Wall
$M(x)$	Magnification function
$T(x)$	Transformation function
V_y	The distance between the viewer and the visual plane of the Perspective Wall
x	A point variable on the horizontal axis
θ	The angle between the perspective wall and the visual plane

Table B.I Variables and notations used in this section

1. Polyfocal Projection (Kadmon & Shlomi 1978)

The transformation function of the Polyfocal Projection is given by,

$$T_{polyfocal}(x) = x + \frac{A \cdot x}{(1 + C \cdot x^2)} \quad (1)$$

where A and C are constants.

The magnification function of the Polyfocal Projection is,

$$\begin{aligned} M_{polyfocal}(x) &= \frac{d}{dx}(T_{polyfocal}(x)) \\ &= 1 + \frac{A \cdot (1 + C \cdot x^2) - A \cdot x \cdot 2 \cdot C \cdot x}{(1 + C \cdot x^2)^2} \\ &= 1 + \frac{A - A \cdot C \cdot x^2}{(1 + C \cdot x^2)^2} \end{aligned}$$

$$M_{polyfocal}(x) = 1 + \frac{A \cdot (1 - C \cdot x^2)}{(1 + C \cdot x^2)^2} \quad (2)$$

2. Bifocal Display (Spence & Apperley 1982)

From Figure B.1, the transformation functions of the Bifocal Display can be derived as follows:

$$\text{for } x \leq a, \quad T_{bifocal}(x) = x \cdot \frac{b}{a} \quad (3)$$

$$\text{for } x > a, \quad T_{bifocal}(x) = b + (x - a) \cdot \frac{(1 - b)}{(1 - a)} \quad (4)$$

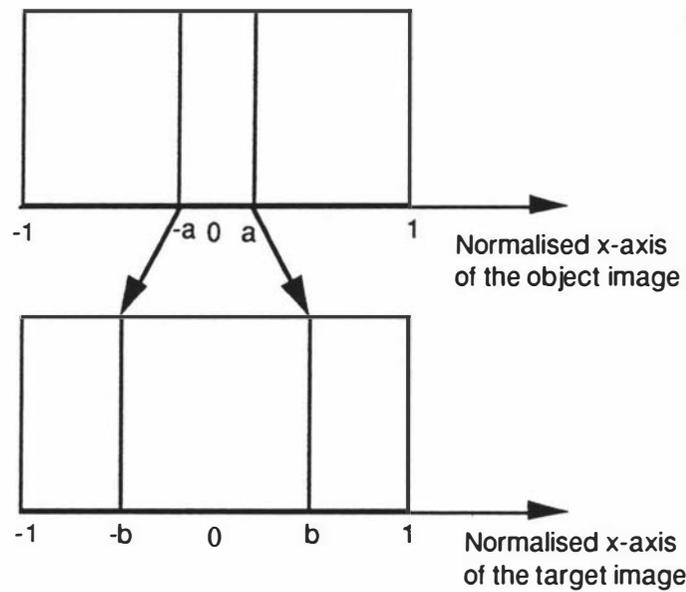


Figure B.1 The relationships between the object image and the target image

The magnification function of the Bifocal Display is:

$$M_{bifocal}(x) = \frac{d}{dx}(T_{bifocal}(x)),$$

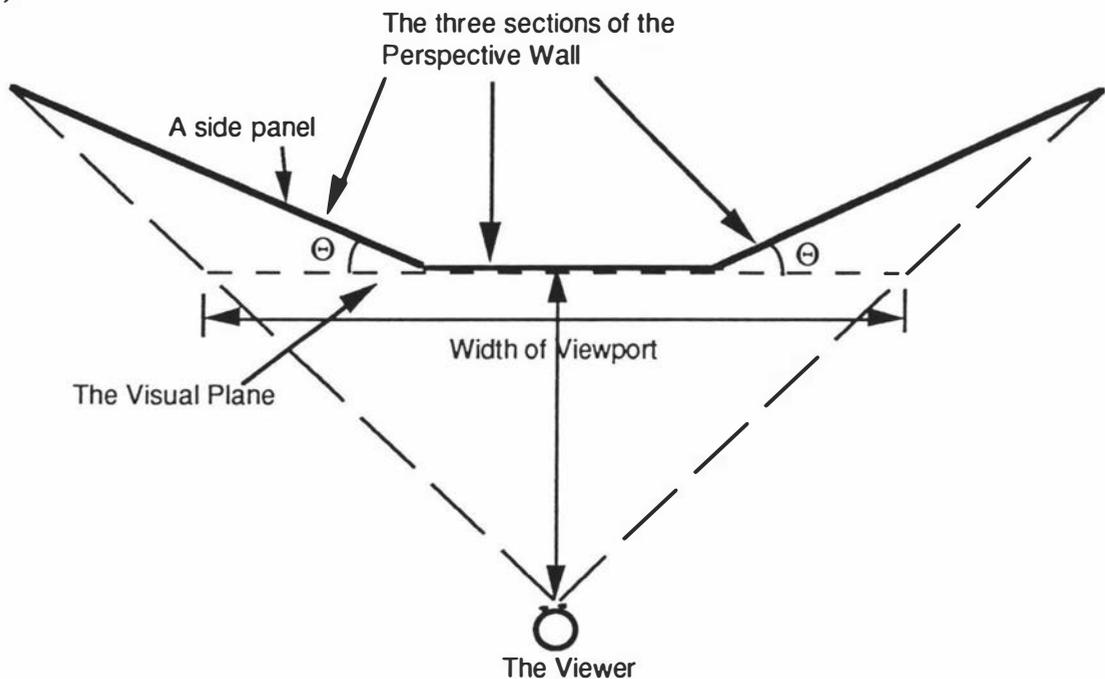
$$\text{for } x \leq a, \quad M_{bifocal}(x) = \frac{b}{a} \quad (5)$$

$$\text{for } x > a, \quad M_{bifocal}(x) = \frac{(1 - b)}{(1 - a)} \quad (6)$$

3. Perspective Wall (Mackinlay *et al* 1991)

Figure B.2 shows an elevated view of a Perspective Wall and the relationships between the object image and target image. Figure B.3 shows a simplified diagram of Figure B.2 with the coordinates of a number of key reference points used to derive the transformation function. In order to derive the transformation function of the Perspective Wall, the position of the viewer with respect to Wall will have to be determined first. The position of the viewer is dependent on the width of the viewport, the length of the side panel of the Perspective Wall and θ , the angle between the side panel of the Perspective Wall and the visual plane (Figure B.2).

a)



b)

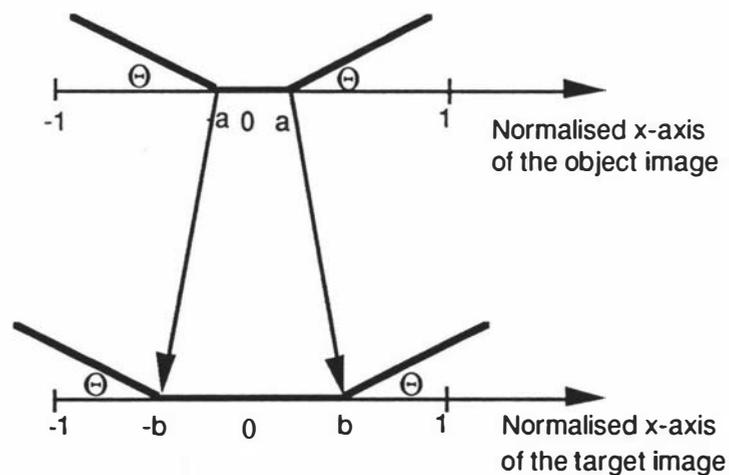


Figure B.2 (a) The physical arrangement of the Perspective Wall
(b) The relationships between the object image and the target image

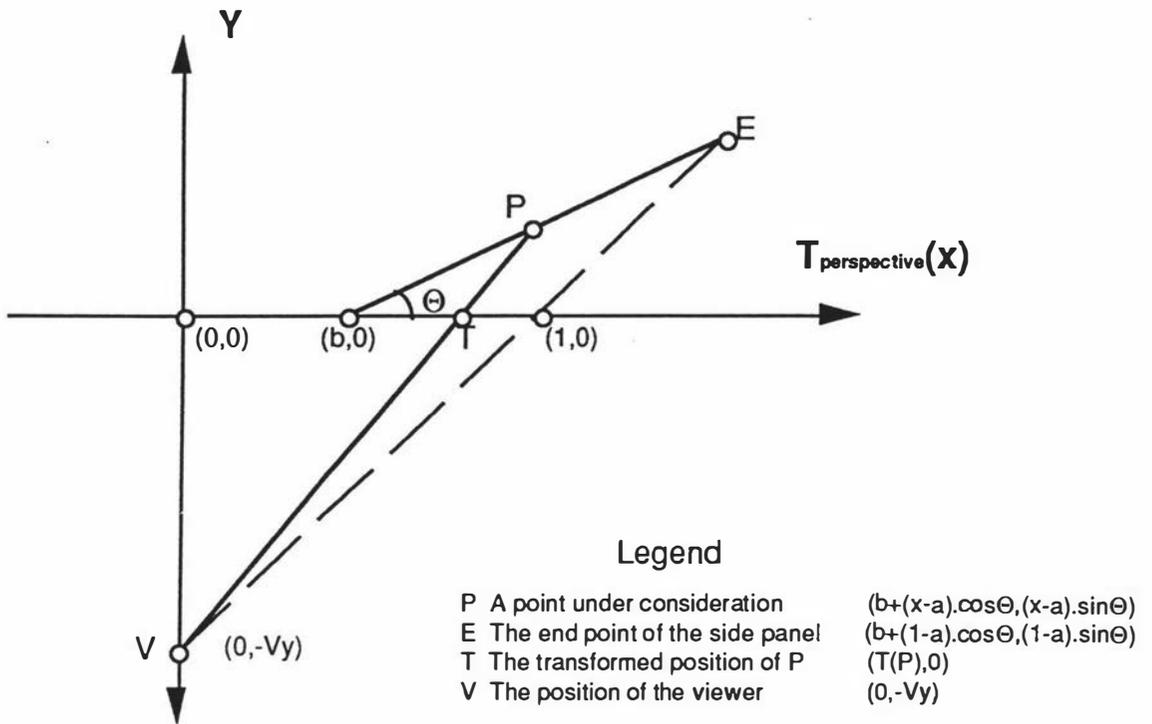


Figure B.3 A simplified elevated view of the Perspective Wall

The position of V can be determined by equating the gradient of the two line segments: V - (1,0) and (1,0) - E (see Figure B.3):

$$V_y = \frac{-(1-a).\sin\theta}{1-[b+(1-a).\cos\theta]} \tag{7}$$

Now, the transformed position of a point P, $T_x(P)$, can be determined by equating the gradient of the two line segments: $T_x(P) - V$ and $P - V$,

$$\begin{aligned} \frac{T_x - 0}{0 - (-V_y)} &= \frac{b + (x - a).\cos\theta - 0}{(x - a).\sin\theta - (-V_y)} \\ T_x &= \frac{V_y.[b + (x - a).\cos\theta]}{V_y + (x - a).\sin\theta} \end{aligned} \tag{8}$$

Substituting (7) in (8),

$$T_x = \frac{\frac{-(1-a).\sin\theta}{1-[b+(1-a).\cos\theta]}.[b+(x-a).\cos\theta]}{\frac{-(1-a).\sin\theta}{1-[b+(1-a).\cos\theta]}+(x-a).\sin\theta}$$

$$T_x = \frac{-(1-a).\sin\theta.[b+(x-a).\cos\theta]}{-(1-a).\sin\theta+(x-a).\sin\theta.\{1-[b+(1-a).\cos\theta]\}} \quad (9)$$

Dividing the numerator and denominator of (9) by $\sin\theta$,

$$T_x = \frac{-(1-a).[b+(x-a).\cos\theta]}{-(1-a)+(x-a).\{1-[b+(1-a).\cos\theta]\}} \quad (10)$$

Dividing the numerator and denominator of (10) by $-(1-a)$ and re-grouping,

$$T_x = \frac{-(1-a).[b+(x-a).\cos\theta]}{-(1-a)+[(1-b)-(1-a).\cos\theta].(x-a)}$$

$$= \frac{[b+(x-a).\cos\theta]}{1-\left[\frac{(1-b)}{(1-a)}-\cos\theta\right].(x-a)}$$

The transformation functions for a general Perspective Wall are therefore,

$$\text{for } x \leq a, \quad T_{\text{perspective}}(x) = x \cdot \frac{b}{a} \quad (11)$$

$$\text{for } x > a, \quad T_{\text{perspective}}(x) = T_x = \frac{[b+(x-a).\cos\theta]}{1-\left[\frac{(1-b)}{(1-a)}-\cos\theta\right].(x-a)} \quad (12)$$

It should be noted that in Mackinlay *et al*'s implementation of the Perspective Wall $a=b$ and hence (11) and (12) become,

$$\text{for } x \leq a, \quad T_{\text{perspective}}(x) = x$$

$$\text{for } x > a, \quad T_{\text{perspective}}(x) = \frac{[a+(x-a).\cos\theta]}{1-[1-\cos\theta].(x-a)}$$

Consider if $\cos \theta = \frac{1-b}{1-a}$, that is $k = \cos \theta$, the denominator of equation (12) simplifies to 1, then equation (12) becomes,

$$T_{\text{perspective}} = b + (x-a) \cdot \frac{(1-b)}{(1-a)}$$

which is the transformation function for the Bifocal Display.

By definition the magnification function of a general Perspective Wall is given by,

$$M_{\text{perspective}}(x) = \frac{d}{dx}(T_{\text{perspective}}(x)),$$

$$\text{for } x \leq a, \quad M_{\text{perspective}}(x) = \frac{b}{a} \quad (13)$$

$$\text{for } x > a, \quad M_{\text{perspective}}(x) = \frac{d}{dx} \left(\frac{[b + (x-a) \cdot \cos \theta]}{1 - \left[\frac{(1-b)}{(1-a)} - \cos \theta \right] \cdot (x-a)} \right) \quad (14)$$

Let $k = \frac{(1-b)}{(1-a)}$ and simplifying (14),

$$\begin{aligned} M_{\text{perspective}}(x) &= \frac{d}{dx} \left(\frac{[b + (x-a) \cdot \cos \theta]}{1 - [k - \cos \theta] \cdot (x-a)} \right) \\ &= \frac{\cos \theta \cdot [1 - (k - \cos \theta) \cdot (x-a)] + [b + (x-a) \cdot \cos \theta] \cdot [k - \cos \theta]}{[1 - (k - \cos \theta) \cdot (x-a)]^2} \\ &= \frac{\cos \theta - \cos \theta \cdot (k - \cos \theta) \cdot (x-a) + b \cdot (k - \cos \theta) + (x-a) \cdot \cos \theta \cdot (k - \cos \theta)}{[1 - (k - \cos \theta) \cdot (x-a)]^2} \end{aligned}$$

Simplifying and re-grouping,

$$\begin{aligned} M_{\text{perspective}}(x) &= \frac{b \cdot k + (1-b) \cdot \cos \theta}{[1 - (k - \cos \theta) \cdot (x-a)]^2} \\ &= \frac{b \cdot k + (1-b) \cdot \cos \theta}{[1 - (k - \cos \theta) \cdot x + (k - \cos \theta) \cdot a]^2} \end{aligned}$$

$$M_{\text{perspective}}(x) = \frac{b \cdot k + (1-b) \cdot \cos \theta}{[(k - \cos \theta) \cdot x + (a \cdot \cos \theta - a \cdot k - 1)]^2} \quad (15)$$

With $a=b$, and therefore $k=1$, the magnification functions of Mackinlay *et al*'s implementation of the Perspective Wall $a=b$ become,

$$\text{for } x \leq a, \quad M_{\text{perspective}}(x) = 1$$

$$\text{for } x > a, \quad M_{\text{perspective}}(x) = \frac{a + (1-a) \cdot \cos \theta}{[(1 - \cos \theta) \cdot x + (a \cdot \cos \theta - a - 1)]^2}$$

However, if $\cos \theta = \frac{1-b}{1-a}$, that is $k = \cos \theta$, the denominator of equation (15) becomes 1, and equation (15) simplifies to,

$$\begin{aligned} M_{\text{perspective}} &= b \cdot k + (1-b) \cdot k = k \\ &= \frac{(1-b)}{(1-a)} \end{aligned}$$

which is the same as the magnification function for the Bifocal Display.

4. Fisheye View (Sarkar & Brown 1992)

The transformation function of the Fisheye View is given by,

$$\begin{aligned}
 T_{\text{fisheye}}(x) &= \frac{1+d}{\left(d+\frac{1}{x}\right)} \\
 &= \frac{(1+d).x}{(d.x+1)}
 \end{aligned} \tag{16}$$

where d is called the distortion factor.

The magnification function of the Fisheye View is, therefore,

$$\begin{aligned}
 M_{\text{fisheye}}(x) &= \frac{d}{dx}(T_{\text{fisheye}}(x)) \\
 &= \frac{(1+d).(d.x+1) - (1+d).x.d}{(d.x+1)^2} \\
 &= \frac{(d.x+1) + d^2.x + d - x.d - x.d^2}{(d.x+1)^2} \\
 M_{\text{fisheye}}(x) &= \frac{d+1}{(d.x+1)^2}
 \end{aligned} \tag{17}$$

5. Summary

Table B.II summarises the transformation and magnification functions of the distortion-oriented techniques derived earlier as follows:

	Transformation Function T(x)	Magnification Function M(x)
Polyfocal Projection	$x + \frac{A.x}{(1+C.x^2)}$	$1 + \frac{A.(1-C.x^2)}{(1+C.x^2)^2}$
Fisheye View	$\frac{(1+d).x}{(d.x+1)}$	$\frac{d+1}{(d.x+1)^2}$
Perspective Wall		
for $x \leq a$,	$x \cdot \frac{b}{a}$	$\frac{b}{a}$
for $x > a$,	$\frac{[b + (x-a).\cos\theta]}{1 - \left[\frac{(1-b)}{(1-a)} - \cos\theta \right].(x-a)}$	$\frac{b.k + (1-b).\cos\theta}{[(k - \cos\theta).x + (a.\cos\theta - a.k - 1)]^2}$
		note: $k = \frac{(1-b)}{(1-a)}$
Bifocal Display		
for $x \leq a$,	$x \cdot \frac{b}{a}$	$\frac{b}{a}$
for $x > a$,	$b + (x-a) \cdot \frac{(1-b)}{(1-a)}$	$\frac{(1-b)}{(1-a)}$

Table B.II A summary of transformation and magnification functions