PACED SERIAL ADDITION:

An Investigation into the Nature of the Cognitive Processes Involved in PASAT Performance

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ABSTRACT

The Paced Auditory Serial Addition Test (PASAT) of Gronwall and Sampson (1974) is a neuropsychological test of attention used in both research and clinical settings (Lezak, 1983). However, a review of the literature revealed that the cognitive processes and attentional factors underlying PASAT performance are not well understood. Two experiments were conducted with the aim of providing further empirical and theoretical insights into PASAT performance. In Experiment 1, 16 subjects (8 male and 8 female) performed auditory and visual versions of a shortened paced serial addition task. It was found that PASAT performance in the visual stimulus modality was superior, but that, as indexed by accuracy and error scores, the pattern of performance as a function of the rate of stimulus presentation (1.2, 1.6, 2.0, and 2.4 s) was similar. These results are consistent with the idea that the nature of the cognitive processing involved is independent of stimulus modality. The design of Experiment 2 was the same as the first, except that divided field stimulus presentation was used in an attempt to test two opposing theories of attention. The results were not consistent with the hypothesis. The findings of both experiments were discussed in terms of the possible role of attention deficits in PASAT performance. An interesting finding was that the superior performance of male subjects in Experiment 1 was reversed in Experiment 2. This differential effect for divided field stimulus presentation as a function of gender may be partly accounted for by differing degrees of cerebral lateralisation for males and females.

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INTRODUCTION

Overview

The Paced Auditory Serial Addition Test (PASAT) was developed by Gronwall and Sampson (1974) for use in studying the psychological effects of concussion. It has since become a widely used neuropsychological test of attention (Gray, Robertson, Pentland, & Anderson, 1992; Lezak, 1983), particularly for head-injured patients. Prior to being used as a clinical test, the paced serial addition task was used by Sampson (1956) to investigate theoretical issues relating to the effect of temporal variables on human performance. The PASAT, then, has the potential to be a useful tool in addressing both theoretical and practical issues and the link between them.

This potential has not been realised, however. Although there exists a large body of experimental findings, these appear to be under-utilised in the practical application of the PASAT. While comprehensive validity and standardisation studies have recently been conducted, theoretical development has been neglected. The PASAT is widely held to be a valuable test of attention and information processing, but research that might help to more precisely delineate the cognitive processes underlying PASAT performance, and perhaps contribute to the general understanding of attentional processes, has not been forthcoming.

The aim of the present study was to investigate the cognitive processes underlying PASAT performance. This was done with both theoretical and practical issues in mind, in an attempt to bridge the gap between research and practice.

The Paced Auditory Serial Addition Test (PASAT)

Authoritative sources (Binder, 1986; Gronwall, 1989, 1991; Lezak, 1983; Szymanski & Lynn, 1992; Tranel, 1992; van Zommeren, Brouwer, & Deelman, 1984) correctly attribute the development of the Paced Auditory Serial Addition Test (PASAT) to the work of a group led by Dr Dorothy Gronwall of the Auckland Hospital Head Injury Unit in New Zealand (Gronwall, 1976a, 1976b, 1977; Gronwall & Sampson, 1974; Gronwall & Wrightson, 1974, 1975, 1981; Ewing, McCarthy, Gronwall, & Wrightson, 1980). Only rarely acknowledged (Gronwall, 1987; Gronwall & Sampson, 1974), however, is that the paced serial addition task was originally developed by Sampson (1956). In turn, Sampson cited the experimental methodologies of Bills (1931, 1935a, 1935b, 1937) and Conrad (1953a, 1953b, 1953c) as being important precursors to the construction of the paced serial addition task.

The task developed by Bills (1931) was self-paced and involved the alternate mental addition and subtraction of the number three from a list of single-digit numbers. Conrad's work (cited in Sampson, 1956) featured the element of "pacing", in that the stimulus display changes on a sensory-motor task were under experimenter, rather than subject, control. Sampson modified and synthesised these approaches to develop the paced serial addition task. His task was one of addition only, and was serial in nature in that it required the addition of each number in a series to the one that came immediately before. Pacing was achieved by presenting the numbers at a predetermined rate. The stimulus materials, a series of 61 randomised single digit numbers from one

to nine, were presented in either the auditory or visual modalities. The products of subjects' mental additions were reported verbally to the experimenter.

The aim of Sampson's (1956) work was to study the effects of varying stimulus exposure durations and "pacing rates" on paced serial addition performance. Initially, Sampson varied the "stimulus on" (stimulus exposure duration, or SD) and "stimulus off" (interstimulus interval, or ISI) stimulus presentation parameters by combinations of 0.4, 0.8, and 1.2 s (Experiment 1) and 0.3, 0.6, and 0.9 s (Experiment 2). Later, Sampson and MacNeilage (1960) reported a series of eight further experiments (Sampson, 1958a, 1958b, 1959; Sampson & MacNeilage, 1959, all cited in Sampson & MacNeilage, 1960) of similar design. As the parameters of interest were more amenable to manipulation in the visual than in the auditory modality of stimulus presentation, the experiments were conducted almost exclusively in the visual modality.

The shift in emphasis to auditory stimulus presentation and clinical use occurred some years later when Gronwall and Sampson (1974) employed the paced serial addition task in their investigation of the psychological effects of concussion. The visual stimulus presentation was judged to be of limited utility in this research because of the incidence of photophobia as a sequelae of concussion (Gronwall and Sampson). In essence, the task was little different from that developed by Sampson (1956) but for the specification of administration parameters, most notably the rate of stimulus presentation. In the Gronwall and Sampson version, the series of 61 digits, following the administration of a short practice trial at the slowest presentation rate, is repeated four times at

progressively faster rates of 2.4, 2.0, 1.6, and 1.2 s per digit. The ISI is inclusive of the SD, which Gronwall and Sampson estimated to be an average of 400 ms for auditory presentation. This point in the history of paced serial addition marked the transition from experimental task to psychometric instrument, known by the acronym, PASAT.

Further development has taken place, mostly in the form of minor modification. According to Roman, Edwall, Buchanan, and Patton (1991), Harvey Levin of the University of Texas Medical Branch in Galveston developed a shortened version of the PASAT in which the stimuli consist of four different series of 50 digits. The aim of these modifications was to shorten the task and to overcome any bias possibly introduced by repetition of a single series of digits. This version, which will be referred to as the Galveston PASAT, is in common use in the USA (Roman et al., 1991). Miller and Gil (1994) also credit Levin with a revised PASAT, called the PASAT-R, in which the number series are of only 26 digits. Some authors (Deary, Langan, Hepburn, & Frier, 1991; Egan, 1988) have also administered the PASAT at an ISI of 4.0 s. A modification of the PASAT which is appropriate for use with children was developed by Johnson, Roethig-Johnson, and Middleton (1988; Dyche & Johnson, 1991a, 1991b). The difference between the children's PASAT, or CHIPASAT, and other versions is simply that none of the additions required on the CHIPASAT have sums greater than 10.

The Digit String Addition Test (DSAT) of Vernon and Weese (1993), although based on the PASAT and sharing many of its attributes, appears to represent a more radical

attempt to shorten and simplify the PASAT. The main differences are that the number sequence used is only 10 digits long, and is repeated three times at rates of 3.0, 2.0, and 1.0 s per digit. The time required to administer the DSAT is therefore a fraction of that needed for the PASAT. As yet there is insufficient data available to evaluate the clinical utility of the DSAT or to compare performance on this test with performance on the PASAT. However, given criticism to the effect that many subjects find the PASAT to be "an aversive, stressful test" (Roman et al., 1991, p. 38) and that even some normal subjects are unable to perform the test at all (Stuss, Stenthem, & Poirier, 1987), the DSAT may be a valuable alternative to the PASAT in some situations. The following discussion of paced serial addition research reviews the findings and theories relevant to the PASAT as it was originally developed and used by Gronwall and Sampson (1974).

PASAT Research

Research involving paced serial addition has taken place in three main chronological periods, but is more easily classified according to the subject population of interest. In the first period of research (e.g., Sampson, 1956, 1961; Sampson & MacNeilage, 1960), the focus of study was the performance of normal subjects. The second period of investigation, carried out by the Gronwall group in the mid to late 1970s (e.g., Gronwall & Sampson, 1974), mainly focused on the impaired PASAT performance of head-injured subjects. The third period spans roughly the decade up to the present time. This period was also mainly concerned with head-injured and other clinical groups, but has seen a return of interest in the performance of normal subjects for the purposes of

standardisation and validity studies.

In the interests of clarity the following review of PASAT research is presented in four sections. The first section discusses and clarifies the nomenclature and types of measures used to quantify paced serial addition performance both in the research literature and in the present study. The next two sections review the findings from research with normal subjects and clinical groups. The final section of the review critically examines the main theoretical accounts used to explain the findings presented in the first two sections.

Nomenclature and Measures

As the nomenclature used to describe aspects of paced serial addition is quite complex, Figure 1 is provided as a point of reference for the discussion. Figure 1 shows a schematic representation of the temporal relationship between three successive stimuli for paced serial addition according to the definitions used by Sampson (e.g., 1956, 1961; Sampson & MacNeilage, 1960). As noted earlier, Sampson was interested in the effect on performance of varying both the "stimulus on" (SD) and "stimulus off" (ISI) durations. As Figure 1 shows, these durations are defined by the onset and offset of the stimuli. The "pacing rate" for a particular trial (a single administration of the number series at a fixed rate of presentation) is a function of both the ISI and the SD (stimulus duration). For example, an SD of 0.4 s, in combination with an ISI of 1.2 s, yields a pacing rate of 1.6 s. These simple relationships, however, were complicated by inconsistent use of the nomenclature in later studies involving the PASAT.

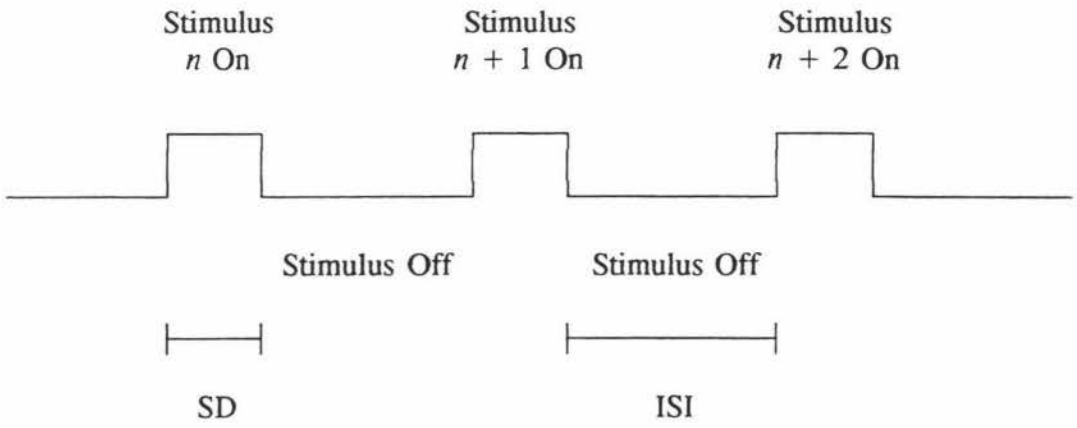

Figure 1. *A diagrammatic representation of the temporal relationship between the "stimulus on" and "stimulus off" durations for paced serial addition. Respectively, these portions are represented by the terms "stimulus duration" (SD) and "interstimulus interval" (ISI).*

With the shift to auditory stimulus presentation associated with the development of the PASAT came a reduction in the emphasis on the SD, because the SD is assumed to be more or less constant for the spoken numbers. This is not strictly true, however, as the duration of the stimulus varies according to which number is being presented. Gronwall and Sampson (1974) estimate the average duration across the digits at around 400 ms. Given this assumption of constant duration for the auditory stimuli, Gronwall and Sampson, and many authors after them, have used the term ISI to describe the duration of the period from the *onset* of stimulus *n* to the onset of stimulus *n* + 1. For the PASAT, therefore, ISI is synonymous with pacing rate.

To avoid confusion, therefore, the present study uses the terms SD and ISI to refer to the temporal relationships between stimuli as depicted in Figure 1, consistent with the

definitions used by Sampson (1956, 1961; Sampson & MacNeilage, 1960). In a similar vein, the interval from the onset of stimulus *n* to the onset of stimulus *n* + 1, which represents the total of SD + ISI, is referred to as constituting the presentation or pacing rate for a particular trial. However, as these terms describe the temporal relationship between stimuli only, an additional term is required to define the temporal relationship between stimuli and responses. As such a term has not previously been used in the literature, one is defined and described below.

The term "response interval" was adopted to describe the temporal relationship between stimuli and responses. This term refers to the interval used for scoring purposes to decide whether or not a response has been given quickly enough for it to be unambiguously associated with a particular pair of stimulus numbers. In reference to Figure 1, the response interval for the addition of the stimuli *n* and *n* + 1 is the period from the offset of stimulus *n* + 1 to the offset of stimulus *n* + 2.

The most commonly employed measure is the number, or more often percentage, of correct responses for a particular trial. This is the measure referred to by the term "accuracy". Although the parameters for a correct response are not always clearly defined (e.g., Sampson, 1956), when they are (e.g., Gronwall & Sampson, 1974), a correct response is generally one that represents a numerically correct addition of digits *n* and *n* + 1, and which is given before or contiguous with the onset of digit *n* + 2, that is, within the response interval. In the present study, this measure will be referred to as CI (correct and inside the response interval).

In some studies the CI score is transformed into a ratio which is expressed as the number of seconds required for each CI response. This score type is abbreviated as SCR (seconds per correct response). For example, if a subject gives CI responses on 40 of the 60 response opportunities on a PASAT trial at the 1.6 s rate, which has a nominal duration of 96.4 s, then the SCR ratio for that subject is 2.41 (96.4/40). Sometimes (e.g., Gronwall & Sampson, 1974), the SCR ratio is averaged across PASAT trials to give an overall index of performance.

In a few studies (e.g., Gronwall & Sampson, 1974; Sampson, 1956) the type and frequency of errors has been used as an additional measure of performance. Three different types of response error can be committed on a paced serial addition task. These can be defined as functions of both the nominal accuracy of the response and its temporal relationship to the following stimulus. For the purposes of the present study the error types and the abbreviations used for each are: responses which are numerically correct but which are given after the offset of the next stimulus, or outside the response interval (CO), and numerically incorrect responses given inside (II) or outside (IO) the response interval. Of course, some limit as to how far outside the response interval a response might fall before it can no longer be said to be associated with a specified pair of stimuli is also necessary. Therefore, a response for digits n and $n + 1$ must fall between the offset of stimulus $n + 2$ and the offset of stimulus $n + 3$ to be counted as falling outside the response interval but still associated with the relevant stimulus pair.

The complete absence of a response, though not technically a response error, is also

used as a performance measure in some studies. In the present study this sort of error is referred to as an omission error (OM). Although the measures discussed may be referred to as if they were separate indices of performance, they in fact represent partitions of a single dependent variable; that is, the total of CI, CO, II, IO, and OM scores must necessarily equal the total number of response opportunities on a trial.

With the nomenclature and types of measures used in the study of paced serial addition clarified, consideration can now be given to the findings from paced serial addition research. In the discussion that follows, attention will first be given to findings relevant to paced serial addition performance as a function of experimental variables, and then to findings in which performance differences as a function of group characteristics are the focus of interest. Although a few studies have investigated such performance changes using subject groups drawn from clinical populations, such as head-injury patients, the majority have used normal subjects. For this reason, the following section reviews the findings for normal subjects only; the findings for clinical populations are considered in a later section.

Empirical Findings for Normal Subjects

The literature reveals a range of fairly distinctive patterns of paced serial addition performance for normal subjects. Many of these emerge as functions of experimental variables such as task duration, SD, ISI, stimulus modality, and repeated performance. In addition, performance has been found to vary with group characteristics such as age, intelligence, and sex.

Performance Changes Related to Experimental Variables

The discussion of performance changes as a function of experimental variables considers a total of seven variables for which the evidence suggests a fairly reliable effect on paced serial addition performance. Much of this evidence comes from the research carried out during the development of the paced serial addition task (e.g., Sampson, 1956). The discussion shows that for many of the performance patterns considered, recent research has done little to improve understanding of the cognitive mechanisms underlying paced serial addition performance.

CI scores by Task Duration

The first pattern of performance change to be considered is the decrease in accuracy with task duration, that is, the within-trial decrement in CI scores across time. Sampson and MacNeilage (1960, Figure 3) demonstrated this effect by plotting performance on trials administered at various ISI/SD combinations in blocks of 10 response opportunities. They observed that the decline in accuracy was greatest during the first 10 to 20 response opportunities, and thereafter continued at a slower rate to the end of the trial. For example, at ISI/SD combinations yielding a pacing rate of 1.2 s, CI scores for the first block were usually around 90%. For the second and third blocks scores declined to about 75% and 70%, and by the last (sixth) block they were down to about 60%. Similar findings for a group of normal subjects were reported by Gronwall and Sampson (1974).

The decline in CI scores with task duration for paced serial addition is probably very

similar to the effects found by Bills (1931) for his addition and subtraction task. Bills found that as task duration increased, so too did the frequency and length of what he called "blocks". These blocks, which he described as mental rest periods, were periods during which the subject seemed unable to respond. As such, they are presumably very similar to OM errors in paced serial addition. The data given by Sampson (1956; Sampson & MacNeilage, 1960) and by Gronwall and Sampson (1974) do not allow such a detailed analysis of within-trial trends in OM errors. However, the second major pattern of paced serial addition performance change to be discussed lends support to the suggestion that the decline in CI scores with task duration in fact reflects increases in both the frequency of OM errors and the length of OM error blocks.

Error Scores by Presentation Rate

Sampson (1956, 1961) found that the frequency of errors other than omissions, which he presents as a single category, tended to increase only slightly with the acceleration of presentation rate. Omissions, however, rose disproportionately as the ISI was decreased. To illustrate, for the 0.8, 1.6, and 2.4 s pacing rates in Experiment 1 (Sampson, 1956) the frequency of errors other than omissions (out of 60 possible responses) never rose above five. The frequency of OM errors, however, went from approximately two at 2.4 s, to about eight at 1.2 s, and to almost 30, or close to 50%, at 0.8 s. The average number of successive omissions also increased with the acceleration of pacing speed. Thus, the second major pattern of paced serial addition performance change does in fact suggest that a decrease in CI scores may be more accurately reflected in the pattern of OM errors.

Gronwall and Sampson (1974) also analyzed error types for a group of normal subjects, but did not include a distinct category for omissions. Their "late response" error category may be similar to omissions, however, as it showed a tendency to rise disproportionately with the acceleration of presentation rate and was responsible for a significant error type x pacing rate interaction effect. The between-trial increase in both the overall frequency of omissions and the average number of successive omissions is highly reminiscent of the within-trial blocking found by Bills (1931), and adds support to the possibility that an increase in the frequency of OM errors is responsible for the within-trial decrease in CI scores as a function of task duration.

CI Scores by Interstimulus Interval

Just as the decrease in accuracy with task duration appears to reflect more subtle trends in the type and frequency of errors, between-trial error patterns are perhaps a more sensitive index of performance change than the decrement in CI scores as a function of shorter ISIs. However, as CI scores as a function of pacing rate (implying variation of the ISI for the PASAT) are the most frequently, and often only, reported performance index in PASAT research, they will be discussed here as the third main area of findings for normal subjects.

The pattern observed in early research is well summarised by the data from Sampson's (1956, Experiment 1, p. 221) first study. For three of the conditions for which CI scores were reported, the 0.8, 1.6, and 2.4 s pacing rates were made up of equal SD and ISI proportions. The mean percentage of correct responses for each

condition, respectively, was 46.5%, 81.9%, and 96.7%, clearly showing the effect of faster pacing rates on CI scores. Note, however, that in this case both the SD and the ISI were varied, and thus it is difficult to estimate to what degree the effect was directly attributable to variation of the ISI.

Later studies (Gronwall & Sampson, 1974; Sampson, 1961; Sampson & MacNeilage, 1960) confirmed this pattern of results for the PASAT. In these examples, the SD remained constant between trials, so any performance changes can be more confidently attributed to variation of the ISI. For example, Gronwall and Sampson (1974, p. 32) report their findings for a group of normal control subjects on five PASAT trials. The pacing rates for these trials decreased by equal increments of 0.4 s from 2.4 to 0.8 s, and the mean SCR scores found were 3.7, 3.5, 3.5, 4.5, and 7.1 respectively. The overall trend is clearly toward decreased accuracy with shorter ISIs. This trend, however, is not consistently toward lower accuracy at shorter ISIs, a fact that warrants further discussion.

The PASAT results for the group of normal subjects in the study by Gronwall and Sampson (1974) indicate that accuracy at the 2.4 s rate (3.7 SCR) is actually lower than at the 2.0 and 1.6 s rates (3.5 SCR for both). This is likely to be the outcome of methodological factors in the administration of the trials. Gronwall and Sampson administered the five trials in such a way that the subjects always began the testing session with either the 0.8 or 2.4 s trial, and performed the remaining trials in either ascending or descending order of ISI. The intermediate trials, therefore, were always preceded by one or other of the extreme presentation rates, and the 1.6 s trial was

always preceded by two faster or slower trials. It is possible that the elevated accuracy shown for the 2.0 and 1.6 s rates is the result of a within-session practice effect, indicating that a degree of methodological caution is necessary in using the PASAT.

More recently, studies using much larger samples of normal subjects have afforded a more reliable evaluation of the effect of ISI on CI scores. Roman et al. (1991) administered the Galveston PASAT to 143 normal subjects. CI scores for all groups were found to vary as a function of changes to the ISI. For example, the mean percentage of CI scores for a group of 62 subjects aged from 18 - 27 years for pacing rates from 1.2 to 2.4 s, respectively, were 57.92%, 72.79%, 79.53%, and 91.68%. Also using the Galveston version, Brittain, La Marche, Reeder, Roth, and Boll (1991) tested 526 normal subjects and analyzed their data according to age, gender, and estimated intelligence. The effect of shorter ISIs on response accuracy was consistent across all groups, and conformed to the established pattern.

A further trend appears in the CI scores quoted above for both the Sampson (1956) and Gronwall and Sampson (1974) studies. There is a tendency for CI scores to not only decrease with shorter ISI, but to do so in a non-linear fashion, as can be observed in the magnitude of the change in CI scores as pacing rate increases. For Sampson's data, the difference in CI scores between the 2.4 and 1.6 s rates is of the order of 14.8%. Between the 1.6 and 0.8 s rates, however, the difference is much greater at 35.4%. Similarly, Gronwall and Sampson's findings give differences in SCR ratios of -0.2, 0, 1.0, and 2.6, with the greatest differences again being observed between the faster pacing rates.

It is possible that this trend towards a non-linear decrement in CI scores as a function of faster presentation rate is the result of an interaction between the first (CI scores by task duration) and second (error scores by presentation rate) patterns of performance change discussed above. Again, the trend is probably more accurately reflected in OM errors than in CI scores. Sampson (1956, Figure 1 and Table III) showed that the frequency of OM errors increases with faster pacing rates, and that the average number of successive OM errors follows the same pattern. As noted earlier, this between-trial trend is strongly reminiscent of the within-trial blocking found by Bills (1931). A possible interaction of these within- and between-trial increases in OM errors may be responsible for the non-linear decrement in CI scores by presentation rate. Indeed, this is the interpretation of the findings arrived at in a later study by Sampson and MacNeilage (1960), who maintained that the rate of increase in OM errors with task duration increases as a function of the speed of pacing, giving rise to a non-linear decrement in accuracy.

Although this non-linear trend is very noticeable in the Sampson (1956) and Gronwall and Sampson (1974) studies, it does not appear in the results of Roman et al. (1991). In fact, these authors performed a trend analysis on their results which indicated that there was a highly significant ($p < .001$) linear relationship between pacing rate and correct responses, and that there were no significant non-linear components. This failure to find a non-linear trend may relate to the fact that the former studies both included trials at 0.8 s, whereas the fastest trial in the Roman et al. study was at the 1.2 s rate. It may be that the 1.2 s trial is not sufficiently fast to show the full extent of any non-linear component in the performance decrement.

In summary, although the effect of shorter ISIs on CI scores is generally very robust and seems to be the measure of choice in PASAT research, it may also be quite a coarse index of performance. Furthermore, whereas the effect is often assumed to be linear, it is probably not. The appearance of linearity is likely due to the methodology used, which often does not include pacing rates capable of showing that the performance decrement becomes increasingly steep at rates faster than 1.2 s. The findings also indicate that methodological factors such as the order in which PASAT trials are administered may influence the results. As the following discussion shows, there is also reason for methodological caution in respect of repeated testing.

Practice

The fourth major finding to be discussed is the marked improvement in performance, or practice effect, that has been found to occur with repeated testing. Sampson (1961) observed the practice effect when he tested subjects on two separate occasions, five months apart. Later authors (Stuss et al., 1987; Stuss, Stenthem, & Pelchat, 1988; Stuss, Stenthem, Hugenholtz, & Richard, 1989) have confirmed the beneficial effect of practice between sessions. Gronwall and Sampson (1974) found that a practice effect also occurred at a third testing session. In their study the effects of practice were found to be attenuated only when a fourth repetition of the PASAT took place more than a month after the initial testing. It might also be assumed, and the inconsistencies discussed above for the Gronwall and Sampson (1974) findings would appear to confirm, that a practice effect could take place within as well as between PASAT sessions. Not all studies, however, have found evidence of a practice effect. For example, Sampson (1961), using unconventional Lansdell revised digits, found no

evidence of a beneficial effect for practice at retest.

CI scores by Stimulus Presentation Duration

Thus far, many of the effects discussed have related to the duration of the ISI, which for the PASAT is equated with pacing or presentation rate. Sampson (1956, 1961), however, also observed effects that were associated with the stimulus exposure duration. In general, paced serial addition performance has been found to be poorer at shorter SDs (Sampson, 1956, 1961; Sampson & MacNeilage, 1960). As Sampson (1956, Tables III & V) shows, however, the effect of SD interacts in a complex manner with ISI, and the level of performance is always most accurately predicted by the sum of SD and ISI, which is effectively the ISI used for PASAT purposes. This pattern of performance change has received little attention since the shift to auditory stimulus presentation, probably because the SD on the auditory task is not easily manipulated.

CI Scores by Stimulus Presentation Modality

Another pattern of performance variation associated with paced serial addition is the stimulus modality effect, briefly mentioned by Sampson and MacNeilage (1960). Citing an unpublished study (Sampson & MacNeilage, 1959), in which they compared performance on the visual and auditory forms of paced serial addition, the authors maintain that subjects showed both less variability and significantly greater accuracy on the visual task. A recent study by Caroselli, Hiscock, Hassan, and Griffin (1993) has supported these findings. The results of this study (to be discussed in detail later) indicated that at equivalent pacing rates, accuracy was significantly better when the stimuli were presented in the visual modality. The level of difficulty only became

approximately equivalent when the visual stimuli were presented at a pacing rate some 15% faster than the auditory stimuli.

Distraction

One finding in Gronwall and Sampson's (1974, Experiment V) study concerned the effect of distraction on the PASAT performance of normal subjects. The condition of distraction was induced by requiring normal subjects to perform concurrently both the PASAT and a bimanual continuous reaction time task. Performance in the distraction condition was significantly poorer than performance on the PASAT alone. The result of this manipulation was that the performance of normal subjects on the PASAT with distraction, in terms of accuracy levels, response to pacing, and the frequency and type of errors made, was virtually indistinguishable from that of concussed patients performing only the PASAT.

Performance Changes Related to Group Characteristics

In the last decade or so an increasing number of validity and standardisation studies concerning the PASAT have been published. This is likely due to Lezak's (1983) listing of the PASAT as a test of mental tracking in her compendium of neuropsychological tests and procedures, and a consequent increase in the use of the PASAT in clinical settings. This gave rise to the need for a greater understanding of the PASAT and more comprehensive performance norms than were then available. In general, these studies have compared PASAT performance with scores on tests and indices of psychological dimensions such as intelligence and memory, or have investigated group differences in

PASAT performance as a function of factors such as age, sex, and years of education. The main findings from these studies are discussed below. All of these studies used only CI scores in their comparisons and analyses.

PASAT and Intelligence

The PASAT scores of normal subjects have been found to correlate significantly with various indices and estimates of general intelligence, such as the Alice Helm 2, the Catteli Culture-Fair test, the Mill-Hill Vocabulary test, and the Ravens Progressive Matrices (Egan, 1988), the Wechsler Intelligence Scale for Children - Revised (WISC-R) Arithmetic subtest (Johnson et al., 1988), the Wechsler Adult Intelligence Scale (WAIS, Kanter, 1984), the Wechsler Adult Intelligence Scale - Revised (WAIS-R) Digit Span subtest (DeLuca, Johnson, & Natelson, 1993; Weber, 1988) and all subtests excluding Digit Span and Picture Arrangement (Deary et al., 1991), estimated WAIS-R Full Scale IQ (Brittain et al., 1991; Roman et al., 1991), and years of education (Stuss et al., 1987; Stuss et al., 1989). However, Johnson et al. found that scores on the WISC-R Vocabulary subtest were not significantly correlated with CHIPASAT performance. In general, though, the correlations found are in the positive direction, that is, higher intelligence or greater education tends to be associated with better PASAT performance. These correlations are usually in the low to moderate range, but can sometimes be as high as 0.73 (Egan, 1988).

Interpretation of these findings is complicated by factors such as the use of unconventional pacing rates, for example, 4.0 s per digit (Deary et al., 1991; Egan, 1988), inconsistency of results on replication (Weber, 1988), the use of very young

subjects (Johnson et al., 1988), and the use of very limited data for estimation of IQ (Roman et al., 1991). The study conducted by Brittain et al. (1991), which compared Galveston PASAT scores with Wechsler IQ estimated from the Shipley Institute of Living Scale for 526 subjects, is the largest reported study concerning the PASAT. Their overall analysis suggested a highly significant association between estimated IQ and PASAT performance. In general, subjects with higher estimated intelligence performed better on the PASAT. The main effect for intelligence, however, was moderated by interactions with factors such as presentation rate and age. For example, the positive relationship between higher intelligence and higher PASAT scores seemed to become more pronounced at faster presentation rates, particularly for the older age groups.

In an attempt to more precisely delineate the association between PASAT and intelligence, Deary et al. (1991) subjected the WAIS-R and PASAT scores of 94 neurologically normal subjects to a principal components factor analysis followed by a Varimax rotation. The analysis yielded three main rotated factors, two of which clearly corresponded to the verbal and performance components of the WAIS-R. Both the 2.0 and 4.0 s PASAT trials administered showed relatively low loadings (0.11 to 0.24) on these factors. Loadings on the third factor, which Deary et al. maintained resembled the "freedom from distraction" factor found in previous analyses of the WAIS-R, were much higher at 0.79 and 0.80 respectively for the 2.0 and 4.0 s trials. The highest loading on this third factor for any WAIS-R subtest was 0.44 for Digit Symbol. The authors concluded that the PASAT did appear to index general cognitive ability to some degree. However, given that PASAT scores were also significantly higher for subjects

who were found to be faster on other measures of information encoding and processing speed, it seemed more appropriate to describe the test as an index of attention and concentration.

PASAT and Memory

Deary et al. (1991) also analyzed the relationship between 2.0 and 4.0 s PASAT trial performance and memory, as indexed by the Rey Auditory Verbal Learning Test (RAVLT). For the 4.0 s PASAT trial, they found significant correlations ranging from 0.27 to 0.50 for all the RAVLT immediate recall trials, recall of the original word-list after interference, and recall after a 30 min delay. Only for the interference word-list was the correlation low and non-significant. For the 2.0 s PASAT trial, only the correlations of 0.22 and 0.28 with RAVLT immediate recall trials 4 and 5, respectively, were significant. All other correlations were less than 0.20. The implication of these findings is that at long ISIs memory factors may play an important role in PASAT performance, but that memory is less important at presentation rates in the range conventionally used in clinical settings.

PASAT and Age

In general, studies comparing PASAT scores across age groups have found that the abilities underlying PASAT performance appear to undergo rapid maturation at around the ages of 8 - 10 years (Johnson et al., 1988), and then deteriorate at around 50 - 60 years (Brittain et al., 1991; Roman et al., 1991). This relationship may interact with intelligence, however, in that the age-related decline in PASAT scores appears to occur

earlier for groups of lower than average intelligence (Brittain et al., 1991).

PASAT and Sex

A number of studies have compared the PASAT performance of male and female subjects. Although Brittain et al. (1991) found a small but significant effect for sex, in that males tended to perform slightly better than females, most studies have failed to find any sex effects (Caroselli et al., 1993; Johnson et al., 1988; Roman et al., 1991). In a study by Stuss et al. (1987), females tended to perform better than males, although not significantly so.

In summary, the findings for research with normal subjects indicate that there are a range of both experimental and group factors that are associated with performance differences in paced serial addition. Some of the experimental findings, such as the effect of task duration on accuracy, the effects of varying SD and ISI on both CI scores and error rates, and the practice effect, appear to be quite robust. Others, like the stimulus modality effect and the dual-task effect, are not so well established and require further investigation. There is evidence of an association between PASAT performance and group variables such as intelligence and age, but the nature of the relationships is clearly complex. The possibility that the factors of memory and sex of subject are in some way correlated with PASAT performance also requires further study. As the following discussion shows, the need for continued research is even more pressing in light of the widespread use of the PASAT in the assessment of neuropsychological impairment.

Empirical Findings for Clinical Populations

Although the paced serial addition task was initially used in experimental work with normal subjects, its current level of popularity is doubtless due to its use in research conducted with head-injury patients. According to Gray et al. (1992), the PASAT "...has become the standard measure of attentional deficit post-head-injury" (p. 98). More recent studies have sought to extend the utility of the PASAT by using it with clinical groups other than head-injured subjects. The focus of clinical studies is normally to quantify and describe the neuropsychological differences between various clinical groups and normal control subjects. The main findings in this area of research are briefly discussed below. Note that concussion, which may itself be classified according to severity, is here considered to be a form of mild head-injury.

The initial findings of the Gronwall group (Gronwall & Sampson 1974; Gronwall & Wrightson, 1974), indicating that concussion patients scored significantly lower than normal control subjects on the PASAT, have since been replicated by others (Levin et al., 1987). However, several studies have not found any differences on PASAT performance between normal subjects and mildly concussed patients (Gronwall & Sampson, 1974; Stuss et al., 1989; Thomas, 1977, cited in van Zommeren et al., 1984). This may indicate that the effects of very mild head injury lie at the limits of the PASAT's sensitivity.

The issue of PASAT sensitivity is not at all clear-cut, however. Some studies have found differences when the effects might be expected to be small. For example, Gronwall and Wrightson (1975) found that the lowering of PASAT scores consequent

to concussion was more pronounced in subjects who had also suffered a concussion in the past, suggesting a cumulative effect for concussion. One study even found that soccer players' PASAT scores and the number of games played tended to be inversely related. This association was presumed to be related to the frequency with which they had headed the ball (Abreau, Templer, Schuyler, & Hutchison, 1990).

In studies of patients who have suffered moderate to severe head injuries the results are more robust. Such patients have been found consistently to perform at well below the level of published norms or matched controls on the PASAT (Meyers, Levin, Eisenberg, & Guinto, 1983; O'Shaughnessy, Fowler, & Reid, 1984; Stuss et al., 1989). Significant impairments have been found for more severely head-injured subjects up to 5 (Levin, Handel, Goldman, Eisenberg, & Guinto, 1985) and 12 years post-trauma (Crossen & Wiens, 1988).

In some studies (Gronwall, 1976a, 1976b, 1977; Gronwall & Wrightson, 1974) PASAT scores have been found to be a more accurate predictor of the duration of recovery from head injury than the more traditional measures of severity, such as the duration of unconsciousness or post-traumatic amnesia (PTA). The predictive power of the PASAT also extends to the severity of symptoms such as headache, impaired concentration and memory, tiredness, and irritability. Low PASAT scores have been associated with greater severity of head injury sequelae such as personality change (O'Shaughnessy et al., 1984).

PASAT scores have been found to discriminate between normal controls and subjects experiencing other neurologic conditions such as whiplash (Radanov, Di Stefano,

Schnidrig, Sturzenegger, & Augustiny, 1993), chronic fatigue syndrome (DeLuca et al., 1993), and multiple sclerosis (DeLuca et al., 1993; Litvan, Grafman, Vendrell, & Martinez, 1988). Robertson (1990) found that PASAT scores were significantly correlated with the degree of left unilateral neglect in patients who, for the most part, had suffered cerebro-vascular accidents. In an investigation of possible neuropsychological deficits in HIV-infected patients (Grant et al., 1993), symptomatic patients were found to perform significantly worse on the PASAT than did either asymptomatic patients or normal control subjects. Of the tests used in this study, the PASAT was the most accurate in correctly classifying HIV-negative and HIV-positive subjects.

In summary, there is substantial evidence for an association between head injury and lowered PASAT scores, with greater severity of injury resulting in more pronounced and reliable impairment of PASAT performance. More recently, other neurological conditions have also been associated with poor PASAT performance. The major limitation of the work done with clinical groups is that most studies have focused only on differences between normal and clinical groups for CI scores as a function of ISI. There are a range of other experimental variables and group factors that might be employed to shed more light on the nature of impaired PASAT performance. In addition, although the research with clinical groups has shown convincingly that performance impairments can result from neurological trauma or disease, few studies go on to deal with the question of why these impairments occur. The following discussion reviews the theoretical accounts that have been proposed to explain both normal and impaired paced serial addition performance.

Theoretical Accounts

Early experimental work with normal subjects revealed a range of quite distinctive patterns of performance for paced serial addition. This work was followed by the clinical application of the task in the form of the PASAT, and the observation of performance differences between normal subjects and various clinical populations. This in turn gave rise to further research into the correlates of PASAT performance. The development of theoretical accounts for paced serial addition observations has followed a similar course, beginning with explanations for the performance patterns seen with normal subjects, and continuing with accounts of the differences found with neurologically impaired groups. As will become evident, however, recent interest in the PASAT has not been paralleled by either the development of new theory or the further application of established theories to account for findings on the PASAT.

In his first publication concerning paced serial addition, Sampson (1956) discussed the theoretical accounts used by Bills and Conrad to explain their findings. Bills (1931, 1935b) initially attributed the increasing frequency omission errors, or blocking, as a function of task duration to an in-built mechanism designed to protect against mental fatigue, much like a pause in physical work might allow some recuperation of the muscles. In a later study, Bills (1937) took this analogy with physical work further and hypothesised that blocking might be related to a reduction in neural efficiency as oxygen supplies became depleted. Indeed, he was able to show that conditions of mild anoxia had a similar effect on the pattern of blocking as did task duration. Conrad (1953a, 1953b, 1953c, cited in Sampson, 1956) framed his explanation in terms of attentional

lapses and "speed stress" brought about by pacing demands.

Sampson and MacNeilage (1960) also viewed paced serial addition performance as being a function of attention. They constructed a temporal integration hypothesis which had its basis in the work of influential theorists such as Broadbent, Hebb, and Mowrer. A core assumption of Sampson and MacNeilage's theory was that much of human behaviour occurs within a syntax, or set of rules, which is largely determined by temporal factors. According to this theory, orderly sequences of behaviour result from the successful temporal integration of all the "elements" of a skill. They also assumed that "unless prevented from doing so..." an individual would produce "...a continuous, unified flow of response" (p. 70). Armed with these assumptions, the authors attempted to account for the disruption of paced serial addition performance associated with variations to the temporal properties of the stimuli and the temporal relationship between stimuli.

According to Sampson and MacNeilage (1960), "...in order for temporally integrated response sequences to be sustained, a variable background of stimulation is required" (p. 73). This variable background of stimulation is said to consist of the non-specific effects of the stimuli, instructions, pacing rate, and pacing change involved in the task, and the random contribution of general environmental stimuli. The failure of temporal integration on paced serial addition, as evidenced by deviations from the "...continuous, correct response sequence on the task" (p. 70), is the result of a failure of sustained attention which causes the "directive" to regress towards randomness. The "directive" is defined as being "...the general neural organization necessary to fulfil task

demands..." (p. 72). By this they meant that the homogenous nature of the stimuli brought about a form of neural habituation that effectively reduces the ability of the stimuli to evoke the necessary cortical response; that is, the level of variability in stimulation is too low to sustain attention.

Sampson and MacNeilage (1960) used this theory to explain what was happening when the frequency of correct responses declined as a function of task duration. Their theory provides for a fairly passive mechanism by which errors occur. Rather than being actively suppressed or interfered with, behaviour simply becomes less integrated because the task provides insufficient stimulation to sustain the attention necessary to perform it. Sampson and MacNeilage saw this as being the fundamental mechanism by which paced serial addition performance underwent a "*...change in direction....*" (p. 75, italics in original) toward randomness. The passivity of this mechanism, however, hardly fits with their assertion that an individual would produce a temporally integrated flow of responses unless *prevented* from doing so (see p. 28 above).

There are further inconsistencies in the reasoning employed by Sampson and MacNeilage (1960). Having stated that regression of the directive is the result of the habituation that occurs when the variable background of stimulation fails to sustain attention, they go on to maintain that breaks in responding may occur "...despite a background of variable stimulation" (p. 74). These breaks, it is said, would be due to "...the regression of the directive to a condition such that the prevailing composition of non-specific stimulation is no longer optimal" (p. 74). At this point their argument seems to become tautological. On the one hand, regression occurs because the

background stimulation is insufficient to sustain attention, and on the other, the background stimulation is insufficient to sustain attention because regression has occurred.

Sampson and MacNeilage (1960) also sought to account for the decrement in performance associated with increased speed of pacing. They proposed that the rate at which the directive regressed as a function of task duration was itself a function of the rate of stimulus presentation. Therefore, the faster the rate of stimulus presentation, the more rapidly performance deteriorates with task duration. The effect of task duration retains its position as the basic mechanism by which errors occur, but becomes one that varies according to the temporal frequency of stimulus presentation. This aspect of their theory, however, seems to be an unnecessarily complicated explanation of the performance decrement associated with faster stimulus presentation, and furthermore, it may be inconsistent with other elements of the theory.

It is not unreasonable to assume that a faster speed of stimulus presentation, which is said to be a component of the background stimulation, would increase the relative variability of the background stimulation. This, according to temporal integration theory, should retard the rate of habituation and regression. The logical prediction would be that the rate of decline in correct responses with task duration should be slower at faster ISIs, but instead the reverse is said to be true. It seems possible, therefore, that the effect of increased rate of presentation is not secondary to the effect of task duration, as Sampson and MacNeilage (1960) would have it, but that it may be a quite independent effect. This possibility does not appear to have been considered by

Sampson and MacNeilage, and the data presented in their Figure 4 (p. 82) do appear to support their contention that task duration and pacing rate are interactive effects. However, the same figure shows that it is possible for an error to occur very early, even at the first or second response opportunity, within a trial. This observation does not contradict their assertion that regression of the directive begins at the outset of the trial and accelerates thereafter, but it is inconsistent with the notion that task duration, which in this case is nearing zero, is a necessary condition for regression to occur. The underlying assumption of this alternative approach would be not that there exists a certain set of conditions under which a unified flow of correct responses will occur, but that there exists a point, defined by the speed of stimulus presentation, at which the individual would be unable to make a CI response at all. Task duration, according to this approach, would only be of relevance at speeds of presentation that allowed correct responses.

Further doubt is cast on temporal integration theory by later findings reported by Sampson (1961). In a study where he used a complex design combining conventional arabic numerals with unconventional Lansdell revised digits within paced serial addition trials, it was observed that the characteristic decrement in accuracy with task duration, which was evident for conventional digits, did not occur with the unconventional digits. He concluded that the additional demands on attention created by having to remember the unconventional digits retarded the regression of the directive. However, performance changes for both types of digits as a function of ISI did conform to the usual pattern. This occurred for the unconventional digits despite the apparent absence of within-trial regression, which would again suggest that presentation rate is an important determinant

of performance change for paced serial addition.

Sampson (1961) does give greater weight to the role of pacing rate in his explanation of the practice effects he observed for conventional digits. He proposes that the ability to integrate the task-relevant information improves with practice. This is because the disruption of memory caused by the change in pacing rate is less on retesting. As theoretical accounts go, however, this one represents a fairly simple *post hoc* speculation as to the mechanism, or mechanisms, underlying the observed practice effect. Sampson does not appear to have tested these speculations.

Sampson and MacNeilage (1960) account for both the effect of SD and the observed difference in performance between visual and auditory stimulus presentation modalities in a similar manner. Their explanation is one based on the notion of rescanning. According to this approach, at longer SDs the subject is able to process the visual stimulus more than once, something that is not possible at shorter SDs. This results in improved processing and greater accuracy at longer SDs. When the SD is the same for both auditory and visual tasks, rescanning is possible in the visual mode but not in the auditory, and so performance in the former is superior.

Given that Sampson and MacNeilage (1960) based their explanations of other findings on temporal and attentional factors, it is a little surprising that they attempted to account for the effects of both SD and stimulus modality in terms of processing efficiency. Although this may be necessary for the former, where shorter SDs result in decreased accuracy when other parameters are held constant, a simpler mechanism might

be responsible for the stimulus modality effect. It is possible that, at equivalent SDs, a visual stimulus is available for processing in its entirety in a shorter time from onset than an auditory stimulus, which is presented over a period of time rather than instantaneously. Sampson and MacNeilage seem to assume that, given sufficient time, the subject rescans the visual stimulus, but it may simply be that the subject is able to perceive and encode the visual stimulus sooner and therefore can begin the other cognitive operations involved in the task earlier. Hence, the response interval for the visual task may effectively be lengthened.

With the development of clinical applications for paced serial addition came new theoretical approaches. These were aimed at explaining performance differences between neurologically impaired and normal subjects. Gronwall and Sampson (1974) adopted Broadbent's (1971) single-channel, limited-capacity information processing model. According to this model, the individual processes information via a single channel which can accommodate only a finite amount of information at any one time, that is, has a limited capacity. When there is an excess of information, a filtering process takes place. The result of the filter is that only as much information enters the channel as can be processed simultaneously, and presumably, some information never enters the channel for processing at all. At the core of Gronwall and Sampson's (1974) account was the assumption that head-injury somehow reduced the channel capacity of the individual, and that this resulted in lower scores on the PASAT at all pacing rates.

Gronwall and Sampson (1974) explicitly stated that their aim was not to test the single-channel limited-capacity model, but rather to investigate the psychological effects

of concussion. However, the series of experiments they conducted, testing performance on choice reaction time, speech processing, and selective attention, did serve to support their position by ruling out a number of alternative explanations for the observations. These alternatives were that the lowered PASAT scores of concussion patients might be due to a reduction in short-term memory (STM) span, prolonged response-production time, motor slowing, reception difficulties that delayed the transfer of information to the processing stage, increased susceptibility to distraction, or the stress and shock resulting from involvement in an accident.

Gronwall and Sampson (1974) concluded that the deficit caused by concussion, and measured by the PASAT, was a limitation of information processing capacity. This limitation, defined as a reduction in "...the rate at which the nervous system can transmit information" (pp. 84-85), was not due to an impaired ability to perform the actual cognitive operations involved in the task. They saw it more as being the outcome of lowered levels of arousal consequent to concussion, which resulted in a general slowing of cognitive processes. The impairment of arousal was thought to be due to diffuse neuronal damage to the reticular system of the brainstem.

However, although Gronwall and Sampson (1974) conclude that lowered PASAT performance is due to a *slowing* in the rate of central information processing, the PASAT is not a direct measure of the speed of information processing. Slowing as such is merely inferred from the test scores. Nor are Gronwall and Sampson's conclusions entirely consistent with their description of the theoretical model they chose to adopt. Whereas Broadbent's (1971) theory appears to imply that information processing is

limited at the point at which incoming information is selected or filtered prior to conscious attention and processing, Gronwall and Sampson's (1974) conclusions seem to implicate a slowing of the post-selection processing as the cause of lowered PASAT performance. The simple single channel limited capacity models have also been criticised on the grounds that they are inadequate to account for many of the more recent findings in the fields of information processing and attention (Freidman & Polson, 1981).

In a more recent discussion of the neuropsychological impairments associated with head injury, van Zommeren et al., (1984) state that the PASAT is "...a task that is clearly aiming at DADs". The term "DADs" refers to the divided attention deficits said to occur when the attentional resources required for a task are divided or overloaded by the task demands, and is a concept taken from Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) two-process theory of attention. According to van Zommeren et al. the demands of the PASAT are such that attention must be divided between "...stimuli, stored memory elements, mental transformations, and responding" (p. 88), and it is this division that is responsible for errors on the PASAT.

Unfortunately, van Zommeren et al. (1984) did not follow this train of thought to its logical conclusion, which would appear to be that head-injured patients are, for some reason, less able than normal subjects to cope with or withstand the division of attention inherent in the PASAT. Instead, they fell back on Gronwall and Sampson's (1974) position and concluded that lowered PASAT performance in head-injured patients came about because such patients, although using the same "...qualitatively normal control

strategy" (p. 89) as normal subjects, did so more slowly.

Summary of PASAT Research

The development of the paced serial addition paradigm, which has its roots in research conducted over six decades ago, can be traced through its major stages to a point where today it is an established and widely used clinical assessment instrument in the form of the PASAT. The research programme associated with the development of the PASAT has established that performance varies as a function of both experimental variables and group factors for normal subjects. However, the evidence for some of these, such as the stimulus modality effect, is limited and requires further investigation. Research with clinical populations has revealed that the PASAT is sensitive to the neuropsychological effects of head injury and a range of other neurological conditions. Recent studies using large numbers of subjects have established comprehensive norms to guide the clinical interpretation of the PASAT. Work in these areas may benefit from a consideration of other than only CI scores as the sole index of PASAT performance.

Theoretical formulations for paced serial addition performance can also be traced through many decades. The most comprehensive of these was that of Sampson and MacNeilage (1960), who explained many of their findings in terms of temporal integration and the failure of sustained attention. Their theory, however, contained a number of inconsistencies and was abandoned in favour of a single-channel, limited-capacity model by Gronwall and Sampson (1974). These authors concluded that the lowered PASAT scores of concussed subjects were the result of slowed information

processing, and applied the theory in a *post hoc* manner to account for their findings. The most recent development in terms of theoretical advancement appears to have been the observation made by van Zommeren (1981; van Zommeren et al., 1984), suggesting that the lowered PASAT scores of head-injured subjects were evidence of divided attention deficits (DADs).

A possible reason for the lack of research into the cognitive processing underlying PASAT performance is because the design of the PASAT does not easily lend itself to the methodologies often used in studies of attention and information processing. It may also be that the processing involved in PASAT performance is more complex than that normally studied by these approaches. Despite the fact that the cognitive processes underlying PASAT performance are poorly understood, there is a general consensus that the PASAT is a valuable test, or even the test of choice (Gray et al., 1992) in the assessment of attentional deficits.

Given that the PASAT is now widely used as a clinical instrument, the need for continued research and theoretical development is indisputable. If assessment and therapy are to advance, the way must first be paved by progress in the form of an improved understanding of the cognitive processing underlying PASAT performance. Questions about why head-injured and other neurologically impaired groups perform poorly on the PASAT can hardly be answered if we do not first understand the nature of PASAT performance in normal individuals. An advance in this understanding is the aim of the present study.

THE PRESENT STUDY

The general aim of the present study was to investigate the nature of the cognitive processing underlying PASAT performance. The earlier review of the research conducted with normal subjects indicated that there are a number of areas in which further investigation is needed, for example, the stimulus modality effect. The nature of this effect appears to be that paced serial addition performance for visually presented stimuli is superior to that for auditory stimuli. Further investigation of this effect may yield information about the cognitive mechanisms underlying PASAT performance.

Furthermore, the review of the research revealed that much potentially valuable information was being overlooked in studies which limited their analysis to a single performance measure. Accordingly, one of the specific aims of the present study was to investigate the stimulus modality effect for paced serial addition using performance measures in addition to the single index - CI scores - normally used.

The Stimulus Modality Effect

There are only two published studies which suggest that performance differences exist between the auditory and visual forms of the paced serial addition task. In the first, Sampson and MacNeilage (1960) state that performance in the visual mode is superior to performance in the auditory mode, and attribute this difference to rescanning of the visual stimulus by the subject. In the second study, Caroselli et al. (1993) found that performance across modalities was only equivalent when the visual stimuli were

presented at an ISI 15% faster than for the auditory stimuli. The authors maintained that this finding was evidence of a modality-specific factor in paced serial addition performance, but did not propose a specific mechanism which might underlie the observed performance difference.

Jerome Caroselli, in a personal communication to the present author, was able to supply a more detailed summary of the hypotheses, method, results, and conclusions of the study by Caroselli et al. (1993). This extended summary is included in Appendix 1, and will be cited here as: Caroselli et al. (personal communication, 1994). As the methodology used by Caroselli et al. (personal communication, 1994) provided the model used in the present study, their study is discussed in some detail.

In their study, Caroselli et al. (personal communication, 1994) hypothesised that PASAT performance was a function of an underlying general information processing capacity, but that modality-specific demands in terms of stimulus presentation might exist. In order to assess this possibility they developed a computer-administered version of the paced serial addition task, which they called the visual addition task (VAT), in which the stimuli were presented visually. They then compared the performance of normal subjects on three variants of the VAT with performance on a more conventional PASAT.

The PASAT used consisted of four 50 digit trials presented in the conventional manner for the auditory task at progressively faster rates of 2.4, 2.0, 1.6, and 1.2 s per digit. Three groups of 16 subjects (8 male and 8 female) each completed the auditory

task and one version of the visual task. The visual task varied according to the rate of stimulus presentation. For VAT1 the presentation rates were the same as for the auditory task. For VAT2 and VAT3 respectively, the presentation rates were accelerated by 15% and 30% relative to the auditory task. The order of presentation for the PASAT and VAT administration was counterbalanced within-groups.

Sex of subject and task order revealed no significant effects, allowing the data to be collapsed across these two variables. Separate 2 x 4 (Mode x Rate) ANOVAS were then conducted for each of the three groups, yielding significant main effects for presentation rate for all groups. In both the auditory and visual modes, response accuracy was lower at faster presentation rates.

Inspection of the results for the VAT1 group (Figure 1, Appendix 1), for which the presentation rate for the auditory and visual modes was the same, shows that accuracy in the visual mode was consistently higher than for the auditory mode at the 2.0, 1.6, and 1.2 s rates. However, at the 2.4 s rate superior performance is seen in the auditory mode, resulting in a significant Mode x Rate interaction effect. The authors concluded that when presentation rates were equated the PASAT became progressively more difficult than the VAT as the ISI decreased.

It is possible, however, that methodological factors may be at least partly responsible for the Mode x Rate interaction effect. In the Caroselli et al. (personal communication, 1994) study, the 2.4 s trial was always administered first. As noted earlier, this bias may have been responsible for a similar lowering of accuracy in the 2.4 s trial relative

to the 2.0 and 1.6 s trials in the study by Gronwall and Sampson (1974). This alone would not explain the differential effect found in the Caroselli et al. study, in that accuracy for the 2.4 s trial was lower than for the 2.0 s trial only in the visual mode. A second possible methodological bias, however, might explain this effect. The authors do not state what, if any, practice trials their subjects were given. If they gave their subjects the conventional auditory practice trial (at the 2.4 s rate) but omitted to include a visual practice trial, then for all subjects the 2.4 s VAT trial would have been the first time they performed the paced serial addition task in the visual mode. The Mode x Rate interaction effect might therefore be due to a lack of practice in the visual mode.

For the group that performed the VAT2 at presentation rates 15% faster than for the PASAT, no significant differences other than that for presentation rate were found, indicating that the levels of response accuracy for the auditory and visual tasks were very similar. There is still a tendency for visual performance for the first (slowest) trial to be lower than that for the auditory mode, while at the other rates it was slightly higher (Figure 2, Appendix 1), and to be lower than for the second visual trial. For the VAT2, however, this trend does not appear to have been strong enough to cause a Mode x Rate interaction effect. Accuracy on the visual task was significantly poorer than for the auditory task when the presentation rate (VAT3) was accelerated by 30% relative to the PASAT. In this case accuracy for the first trial was superior to that for the second trial, suggesting that methodological factors such as order and practice might also interact with a ceiling effect that became less pronounced at faster visual stimulus presentation rates.

There are a number of other shortcomings in the study by Caroselli et al. (personal communication, 1994) in addition to the possible methodological biases. For one, the only index of performance used was the number of CI responses. The effect of stimulus modality on other indices of performance is therefore unknown. In addition, the authors do not state whether the SD for both modalities was equivalent. The findings of Sampson (1956) indicate that this variable has an important effect on paced serial addition performance. Furthermore, the authors do not state whether the ISI was timed from the onset or offset of the stimulus, so it is impossible to know what the overall ISI was.

Inconsistencies are also present in the conclusions drawn by Caroselli et al. (personal communication, 1994). Their conclusion that a general information processing capacity underlies performance on both the auditory and visual forms of paced serial addition is not supported by either their finding or their interpretation of the Mode x Rate interaction effect for the VAT1 group. Furthermore, their speculations to the effect that the factors that limit PASAT performance in head-injured subjects might be modality-specific, such as "limitations of auditory working memory or interference between the aural stimuli and the patient's oral responses" (p. 2), were not, in fact, tested by their study.

It appears that the superiority of paced serial addition performance in the visual stimulus presentation modality, while demonstrated, remains poorly understood. What is required is an investigation of the stimulus modality effect that affords a greater range and depth of analysis. Experiment 1 of the present study, therefore, was designed to

replicate, clarify, and extend the study by Caroselli et al. (personal communication, 1994). The assumptions and hypotheses adopted for the replication attempt are described in the following section.

Assumptions and Hypotheses

The underlying assumptions adopted in the present study were the same as those of Caroselli et al. (personal communication, 1994). That is, that a general information processing capacity underlies paced serial addition performance in both the auditory and visual stimulus modalities, but that a modality-specific factor gives rise to superior performance in the visual modality. By replicating the Caroselli et al. study, the present study aimed to achieve a clearer understanding of the stimulus modality effect for paced serial addition.

The replication of the study by Caroselli et al. (personal communication, 1994) was partial in that only one condition, in which the stimulus presentation rate was equivalent for both stimulus presentation modalities, was planned. The clarification was to be achieved by controlling for the possible methodological biases present in the original study. The Caroselli et al. study was extended by comparing performance across stimulus presentation modalities using indices of performance in addition to the CI scores obtained in the original study, and as a function of variables other than pacing rate.

Within the context of past findings and the assumptions adopted for the present study,

it was possible to make predictions as to the expected patterns of results for Experiment 1. The first hypothesis was that, under equivalent conditions of pacing, paced serial addition performance in the visual stimulus presentation modality would be superior to performance in the auditory modality, that is, that a stimulus modality effect would be found. This prediction was tested in a comparison of CI scores as a function of presentation rate. The hypothesis would be supported by the finding of a significant main effect for Mode in the predicted direction, and would be contradicted by a Mode x Rate interaction effect. Based on the findings of Caroselli et al. (personal communication, 1994), it was expected that the level of CI scores in the visual modality would be about 15% greater on average than in the auditory modality.

The second hypothesis was that despite the superiority of performance in the visual mode at equivalent presentation rates, performance in both the auditory and visual modes of stimulus presentation is a function of the same underlying form of information processing. Three comparisons were planned as tests of this hypothesis. The first involved a comparison of CI scores as a function of presentation rate. It was predicted that the pattern of responding across presentation rates would be similar for both the auditory and visual tasks, being consistent with the idea that the processing mechanisms functioned in a similar manner.

The second comparison involved an analysis of the frequency of all errors and the pattern of omissions as a function of presentation rate. It was predicted that the frequency of all error types (CO, II, IO, and OM) would be higher at faster rates of stimulus presentation, but that an increase in the frequency of omissions (OM) would

account for a disproportionate amount of this rise, and that this pattern would be similar in both the auditory and visual modes of stimulus presentation. Support for the hypothesis would take the form of significant main effects for Rate for each of the error types in the expected direction, a significant main effect for Error Type, and a Rate x Error Type interaction showing a disproportionate rise in omissions.

The third comparison involved the distribution of correct (CI) responses within trials. It was predicted that accuracy would decrease as task duration increased, and that this pattern would occur for both the auditory and visual modes of stimulus presentation. The hypothesis would be supported by the finding of a significant main effect for Block (sections of 10 successive digit pairs) in the absence of a Mode x Block interaction effect.

It was decided to include sex of subject as a factor in Experiment 1 because it was a part of the analysis conducted by Caroselli et al (personal communication, 1994). While these authors found no effect for sex of subject, a study by Brittain et al. (1991) found that the PASAT performance of males was significantly superior to that of females, although not overwhelmingly so. The present analysis was limited to a comparison of the CI scores for males and females as a function of the Rate and Mode of stimulus presentation.

GENERAL METHOD

The method devised for Experiment 1 was later adapted for use in Experiment 2 of the present study. As the changes required were relatively minor, the methodological elements that the two experiments had in common are described here in a General Method section. Methodological factors that were particular to only one experiment are described in a smaller Method section provided for each experiment. As the earlier review of the research suggested that some of the studies discussed contained methodological shortcomings, these potential flaws and the way in which they were controlled in the present study is described in the following paragraphs.

Methodological Issues

Taking into consideration the findings from early PASAT research and the more recent work of Caroselli et al. (personal communication, 1994), it is clear that a high degree of methodological rigour is required in any attempt to compare auditory and visual paced serial addition performance. Accordingly, the following methodological issues and possible confounds were given particular attention: bias due to the repetition of the same number series, modality or presentation rate order effects, the effect of variability in stimulus exposure duration, within-session practice effects, and the equivalence of pre-testing practice trials. An additional concern was that subject response strategies, such as only responding to every second digit pairing at the faster presentation rates (Norman, personal communication), might bias the results. Although not all of these factors are known for certain to contribute to error, there seemed to be

sufficient evidence to justify caution where each was concerned.

The present study also departed from the conventional methodology and scoring used for the PASAT in three important ways. Firstly, the conventional PASAT uses the digits from one to nine inclusive in its number series, but with auditory presentation this introduces a discrepancy in stimulus presentation duration, in that the number seven is of two syllables and requires a longer time to enunciate than any of the other digits (450 ms as compared to a range of 250-350 ms for the other digits). Rather than risk distorting the sound of the digit by compressing its vocalisation to bring it within the range of the other digits, a decision was made to exclude the number seven from all the number series used, both for the auditory and the visual trials. Secondly, a change to the scoring system was made in view of the observation that a response to the final digit pair could never fall outside the ISI, as no response interval was defined by the presentation of another digit. Accordingly, responses to the final digit pair for each sequence were excluded from all analyses.

Finally, in light of the assertions made by some authors that the PASAT can be an aversive and stressful task, the overall length of the trials was reduced. This was achieved by shortening the trial duration so that each subject could perform one trial at each presentation rate for both stimulus presentation modalities without the total session duration becoming twice as long as for the conventional PASAT. Thus, instead of the normal 61 digit sequence, only 32 digit sequences were used. As the final response was not included in the analysis, each trial consisted of a total of 30 response opportunities. In addition, subjects were given any reassurance thought necessary to avoid elevated

levels of stress or anxiety.

Subjects

The subjects were right-handed male and female undergraduate university students who were unfamiliar with the PASAT. Participation was voluntary and recruitment was through approaches to groups of students in laboratory and tutorial classes in the Department of Psychology at Massey University. Subjects were required to have normal hearing and vision and an absence of any history of head injury for which medical attention was received. Handedness was assessed with the Edinburgh Handedness Inventory (EHI, Oldfield, 1971; Appendix 2). Subject age was also recorded. Number series and the sequence of mode and rate presentations were randomly assigned for all subjects (see Presentation Schedule: Appendix 3), within certain restrictions (see below).

Design

A 2 (Mode: auditory and visual) x 4 (Rate: 1.2, 1.6, 2.0, and 2.4 s) within-subjects design was used. Each subject performed one 32 digit trial at each of the eight possible Mode x Rate combinations. A total of 16 different number series were used, four at each presentation rate (see below for details of series construction). Of the four series used at each presentation rate, each subject was exposed to two, one in the auditory mode and one in the visual mode. The assignment of Mode, Rate and number series was random with the following restrictions:

a) Each of the eight possible Mode x Rate combinations appeared at Trial 1 for an equal number of subjects, that is, twice over 16 subjects;

b) A maximum of three consecutive trials in the same (auditory or visual) mode was allowed for any subject;

c) Each subject was exposed to eight different number series across the eight trials;

d) Over the total of 16 subjects, each of the 16 number series was employed with equivalent frequency for each mode, that is, eight times - four auditory and four visual.

Response Recording and Scoring

Subject responses were recorded both manually by the experimenter on the Subject Response form (Appendices 4 & 5) and on videotape. For the auditory task, both the stimulus numbers and the subject responses were simultaneously recorded via a mixer on separate audio tracks of a videotape. For the visual task the stimulus numbers and the subject responses were simultaneously recorded on the video and audio tracks, respectively, of the same videotape.

All scoring procedures took place outside the experimental session, including scoring of the EHI. Initial scoring of the paced serial addition trials was performed with the aid of the Scoring Template (Appendix 6), and scored for nominal accuracy, that is, responses were marked as correct if they matched the answer given on the Scoring Template, whether or not they had fallen within the appropriate ISI. The second phase of scoring was carried out by playing the videotape recordings back in real time and

deciding whether each response had fallen inside the interval or contiguous with the following stimulus, or outside the interval.

The videotape recordings were also used to perform a check on the accuracy of the experimenter's manual response recording and scoring. An additional random sample of trials were scored by an assistant according to the stated procedure. The inter-rater reliability coefficient was calculated by dividing the number of between-rater agreements by the number of agreements + disagreements (Miller, 1980). The resulting coefficient was .97.

Series Construction

The number series, each consisting of 32 randomly ordered digits from one to nine excluding seven, were constructed with the aid of a computer. The strategy used was to generate a greater number of series than were required, from which were selected those judged to be best balanced. This balancing had two aims: to ensure that each number appeared with about equal frequency in each series, and to ensure that the magnitude of the sums required for each series was about equally divided between single and double digit answers.

For the 16 series selected (512 digits in total) the frequency with which each of the eight digits appeared (mean = 64) ranged from 63 to 69. Within each series, each digit appeared a minimum of three times and a maximum of five times. Again, across the 16 series, the frequency of single and double digit answers was equally divided, at 248 of

each, and within each series there was a range of 14 to 17 of each.

Auditory Task

The auditory stimuli were laid down on 16 standard audio cassette tapes by a digitised computer voice. Generating the stimuli in this manner ensured that the quality, intonation, and duration of each stimulus number was standardised. The mean duration of each stimulus number was 300 ms, and the ISI ran from the offset of stimulus *n* to the onset of stimulus *n* + 1 (see Figure 1, p. 7). The SD and ISI were accurate to within 100 ms.

Visual Task

The computer-generated visual stimuli were displayed on a standard 14" monochrome green screen at a distance of 1 m from the subject. Each stimulus number was 12.0 mm wide and 18.0 mm high. The SD and ISI were the same as for the auditory task. Again, the SD and ISI were accurate to within 100 ms.

Apparatus

The apparatus initially required for the construction of the auditory stimulus materials wAS an Apple MacIntosh Computer with a high quality synthesised voice output connected to a standard stereo audio cassette recorder. A special purpose programme was written to control the voice output to produce each of the number sequences used

with the correct ISIs. A total of 18 audio cassettes were required, one for each of the 16 number series, and one for each of the auditory practice trials.

Figure 2 provides a schematic representation of the apparatus used for the auditory trials. The stimulus numbers were played on the tape deck and were heard by the subject via a pair of standard headphones. A second output from the tape deck went to the eight track audio mixer, from which separate outputs went to the experimenter and to the video recorder.

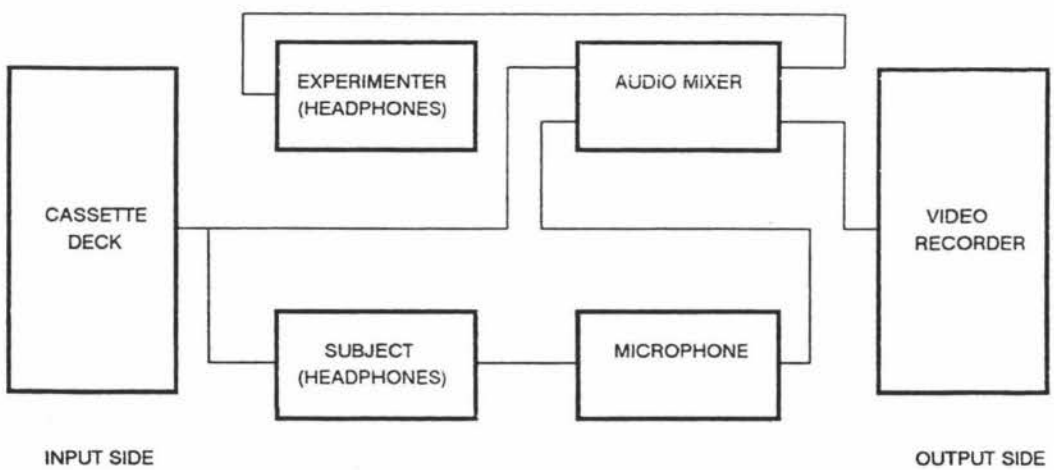

Figure 2. *Schematic diagram of the apparatus used for the presentation of the auditory stimuli and the recording of subject responses in both Experiments 1 and 2.*

Figure 3 provides a schematic representation of the apparatus used for the visual trials. The stimulus numbers were generated by a Hewlett Packard 9000 Series 300 computer and directed simultaneously to two 14" monochrome video monitors (via the

Hewlett Packard 6944 Multiprogrammer for Experiment 2 in order to achieve accurate timing [± 1 ms] of the brief stimulus exposure duration). The image on Monitor 3 was recorded on the videotape via a video camera. Monitor 4 was the screen on which the subject viewed the visual stimuli. Only Monitor 4 was visible to the subject. Monitor 2 was used by the experimenter to programme in the number series and presentation rate required for each visual trial. Monitor 1 was a video output from the video recorder and enabled the experimenter to ensure that the visual stimuli were being recorded accurately and clearly.

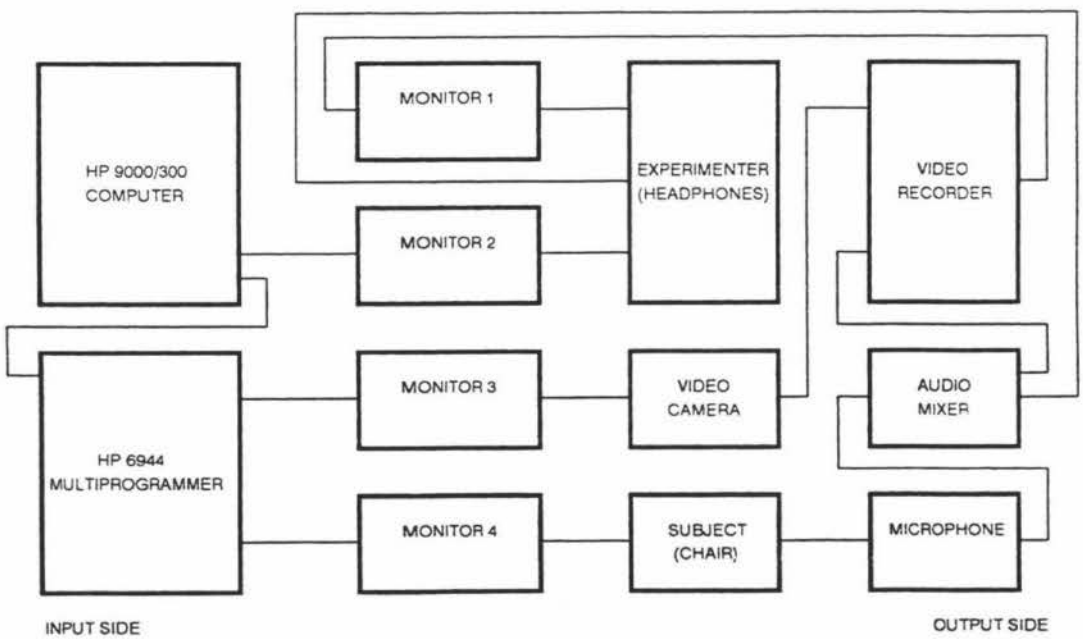

Figure 3. *Schematic diagram of the apparatus used for the presentation of the visual stimuli and the electronic recording of subject responses in Experiments 1 and 2. The Hewlett Packard 6944 Multiprogrammer was used only in Experiment 2 for the accurate timing of stimulus duration (± 1 ms).*

For both the auditory and visual tasks the subject responses were directed to the audio mixer via a microphone. Separate outputs from the audio mixer were used to pass the responses on to the experimenter and to the video recorder.

Analysis

All analyses were conducted using the Statistical Package for Social Sciences (SPSS-PC+) for personal computer (SPSS, INC, 1992). In addition, effect sizes for the F statistic were calculated in accordance with the method set out by the American Psychological Association (APA, 1994). For example, for an F ratio based on v_1 and v_2 degrees of freedom, the magnitude of effect, as indexed by eta squared (η^2), was calculated using the formula $\eta^2 = v_1 F/(v_1 F + v_2)$. The value of η^2 is the proportion of the variance accounted for by the associated effect.

Procedure

Subjects were tested individually, and all sessions took place between 1pm and 5pm in the same laboratory setting. On arrival the subject was asked to read the Information Sheet (Appendix 7) and sign the consent and feedback form (Appendix 8). If the subject consented to continue, the experimenter elicited and recorded the information required on the Subject Information Questionnaire (Appendix 2), which included the EHI.

The experimenter then explained the procedure and task to the subject by reading out the instructions appropriate to the experiment in which the subject was participating

(Appendices 9 & 10). This process included the administration of the eight-digit practice trials in both the auditory and visual modes. Any anxiety or questions raised during the introduction to the procedure and equipment were addressed. If the subject was willing to continue, the experimental trials were administered according to the Presentation Schedule (Appendix 3).

The subject was told which mode and rate would be employed prior to the start of each trial, and was given a brief (30 s) break between trials. Before every trial the subject was encouraged to respond as quickly and accurately as possible, and positive verbal reinforcement was given at the end of each trial. Instructions to avoid partial response strategies were reiterated prior to each trial.

At the end of the experimental session the subject was given positive feedback. For example, "You did really well, you managed to concentrate all the way through and you were more accurate than I would have expected". The subject was then thanked for participating and dismissed. Total session time, including 7 - 10 mins induction, 7.5 mins of trials, 3.5 mins of breaks, and 2 - 4 mins of closure, was from 20 to 25 mins.

EXPERIMENT 1

Method

The subjects were eight males and 11 females. One female subject found the task too stressful and withdrew from the study. An equipment malfunction resulted in the loss of visual input to the video recorder for two female subjects. The records for these three subjects were excluded from the analysis. The mean age for all subjects was 23 years (males = 23.9, females = 22.1). The mean handedness quotient for all subjects was 88.06% (males = 83.88%, females = 92.25%). Subject selection, apparatus, and procedure were as described in the General Method section. Two practice trials, one in each stimulus modality, were given at the 2.4 s presentation rate. For the auditory task, the subject heard each stimulus number in both the left and right ears simultaneously, using a pair of mono headphones. For the visual task, the stimulus numbers were displayed in the centre of the monitor. The duration of each visual stimulus, at 300 ms, was equivalent to the average duration of the auditory stimuli.

Results

The results are presented according to the hypothesis tested and the score type or pattern of responses under analysis. The error type, IO, which was for numerically incorrect responses made outside the response interval, was found to occur at a frequency so low as not to be amenable to meaningful analysis. In four of the eight Mode x Rate combinations, none of the 16 subjects committed an IO error. Rather than

exclude these data from the analysis, they were combined with the category II, or numerically incorrect responses made inside the interval, and analyzed as a single category for numerically incorrect responses (INC). All scores are given as the number of responses, or non-responses in the case of omissions, out of 30 response opportunities unless otherwise stated.

Hypothesis 1

The first hypothesis was that paced serial addition performance in the visual stimulus presentation modality would be superior to performance in the auditory modality when administered at an equivalent presentation rate. Table 1 gives the mean scores for correct responses made within the interval (CI) as a function of the Mode and Rate of stimulus presentation for all subjects.

Table 1. *Mean frequencies (M) and standard deviations (s.d.) for responses scored as correct and falling within the response interval (CI) for all subjects as a function of the mode and rate of stimulus presentation.*

	Presentation Rate							
	1.2		1.6		2.0		2.4	
Mode	M	s.d.	M	s.d.	M	s.d.	M	s.d.
Auditory	13.25	4.06	18.00	4.35	20.13	4.24	24.19	2.88
Visual	17.00	5.65	22.38	5.25	24.94	3.62	26.69	2.92

Figure 4 shows the mean values from Table 1 and graphically illustrates that the level of CI scores is consistently higher in the visual than in the auditory mode of stimulus presentation. The data were submitted to a 2 x 4 (Mode x Rate) within-subjects MANOVA (Appendix 12A). The analysis revealed a significant main effect for Mode, $F\,(1,15) = 47.19$, $p < .001$, $\eta^2 = .76$. On average, using the scores for the auditory task as a baseline, scores for the visual task were 21.7% higher. The absence of a significant Mode x Rate interaction effect, $F\,(3,45) = 0.98$, $p > .05$, indicates that the observed superiority of responding in the visual modality was stable across presentation rates.

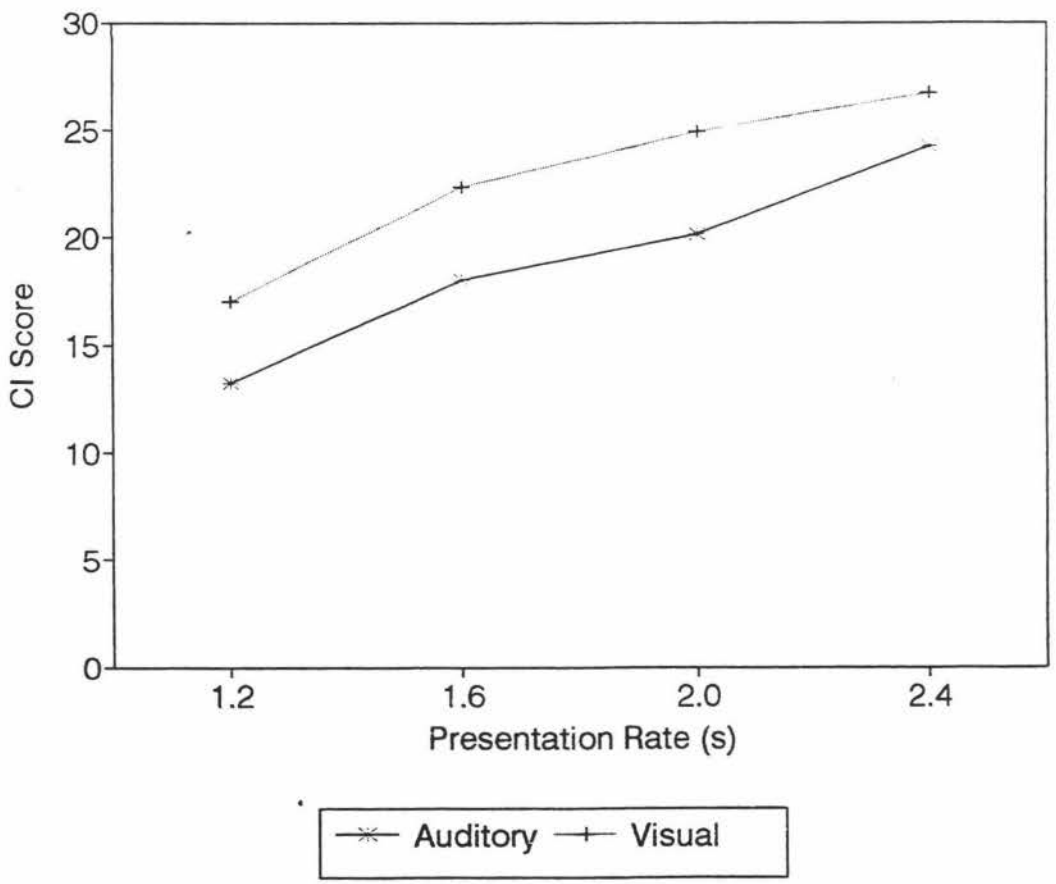

Figure 4. *Mean frequency of correct responses falling within the response interval (CI) for all subjects in the auditory and visual stimulus presentation modalities as a function of presentation rate.*

Hypothesis 2

The second hypothesis was that despite the superiority of performance in the visual mode at equivalent presentation rates, performance in both the auditory and visual modes of stimulus presentation would show a similar pattern of change across measures and variables. The results relevant to each of the three comparisons planned as tests of this hypothesis are presented below.

CI Scores by Presentation Rate

Figure 4 shows that the frequency of CI responses is higher at longer ISIs, that is, response accuracy declines as presentation rate increases. As might be expected from the data in Table 1, the analysis revealed a significant main effect for Rate, $F\,(3,45) = 92.50$, $p < .001$, $\eta^2 = .86$ (Appendix 12A), which was stable across the stimulus presentation modalities.

Error Scores

As noted above, the number of error types analyzed was reduced from four to three in light of the low frequency of IO errors. The means and standard deviations for each of the error types CO, INC, and OM according to stimulus presentation rate and modality are given in Table 2 below. Separate 2 x 4 (Mode x Rate) within-subject MANOVAs were conducted for each error type.

Table 2. *Mean frequencies (M) and standard deviations (s.d.) for three types of error score: nominally correct responses given outside the response interval (CO), nominally incorrect responses (INC), and omissions (OM), as a function of the mode and rate of stimulus presentation.*

		Presentation Rate							
		1.2		1.6		2.0		2.4	
Error Type	Mode	M	s.d.	M	s.d.	M	s.d.	M	s.d.
CO	Auditory	1.19	1.11	1.25	1.61	1.06	1.12	0.69	0.87
	Visual	2.19	1.83	1.89	1.17	0.56	1.03	0.31	0.60
INC	Auditory	2.50	2.10	2.50	2.10	1.88	1.75	2.00	1.37
	Visual	1.81	2.71	1.75	1.95	1.50	1.46	1.31	1.49
OM	Auditory	13.06	4.37	8.25	4.44	6.94	4.30	3.13	2.83
	Visual	9.00	4.29	4.69	4.22	3.00	2.88	1.69	2.21

The analysis for the CO error type revealed a significant main effect for Rate, F (3,45) = 8.07, $p < .001$, $\eta^2 = .35$ (Appendix 12B). The data for the mean frequency of CO errors are shown in Figure 5. Here, it can be seen that the frequency of CO errors tends to be higher at shorter ISIs. However, Figure 5 also illustrates the Mode x Rate interaction effect found, F (3,45) = 3.80, $p < .02$, $\eta^2 = .20$. The effect of shorter ISIs on CO errors in the auditory mode, while in the expected direction, appears

to be quite small. In the visual mode, however, the effect is much more pronounced.

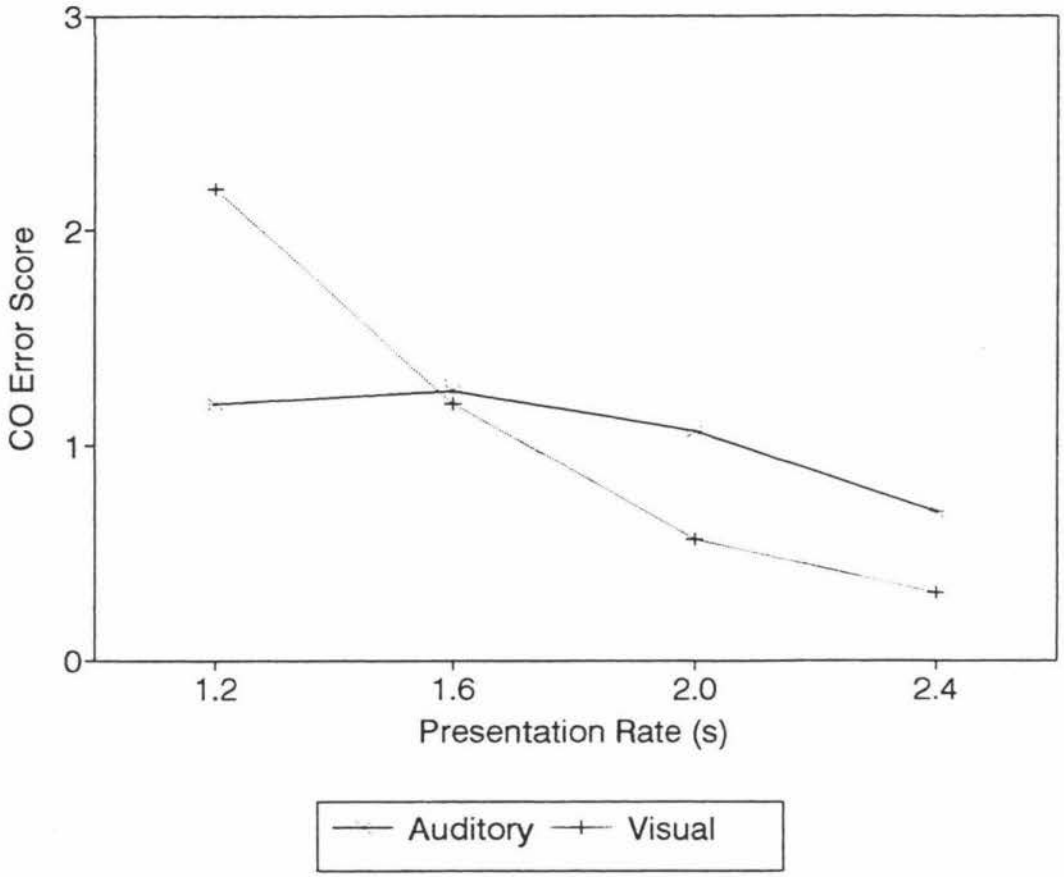

Figure 5. *Mean frequency of numerically correct responses falling outside the response interval (CO) for all subjects in the auditory and visual stimulus presentation modalities as a function of presentation rate.*

The nature of the interaction effect is that at longer ISIs subjects tended to make more CO errors in the auditory mode, but that at the 1.6 s rate the frequency of CO errors was approximately equal and at the 1.2 s rate the pattern had reversed and subjects were more likely to make CO errors in the visual mode. It should be noted that the mean frequency of CO errors, even at its highest point in the visual 1.2 s condition, was only a little more than two responses.

The INC error type occurred at a similar overall mean frequency as the CO error type, reaching a peak of 2.5 responses in the auditory mode at the 1.2 and 1.6 s presentation rates, but the pattern of INC errors across rates was less complex. Although a slight trend toward lower mean frequencies at longer interstimulus intervals can be observed in Figure 6, there was no main effect for Rate, $F\ (3,45) = 0.80$, $p > .05$. The uniformly higher mean level of INC errors in the auditory mode resulted in a significant main effect for Mode, $F\ (1,15) = 5.91$, $p < .03$, $\eta^2 = .28$, but in the absence of a Mode x Rate interaction effect, $F\ (3,45) = 0.13$, $p > .05$ (see Appendix 12C for the INC MANOVA).

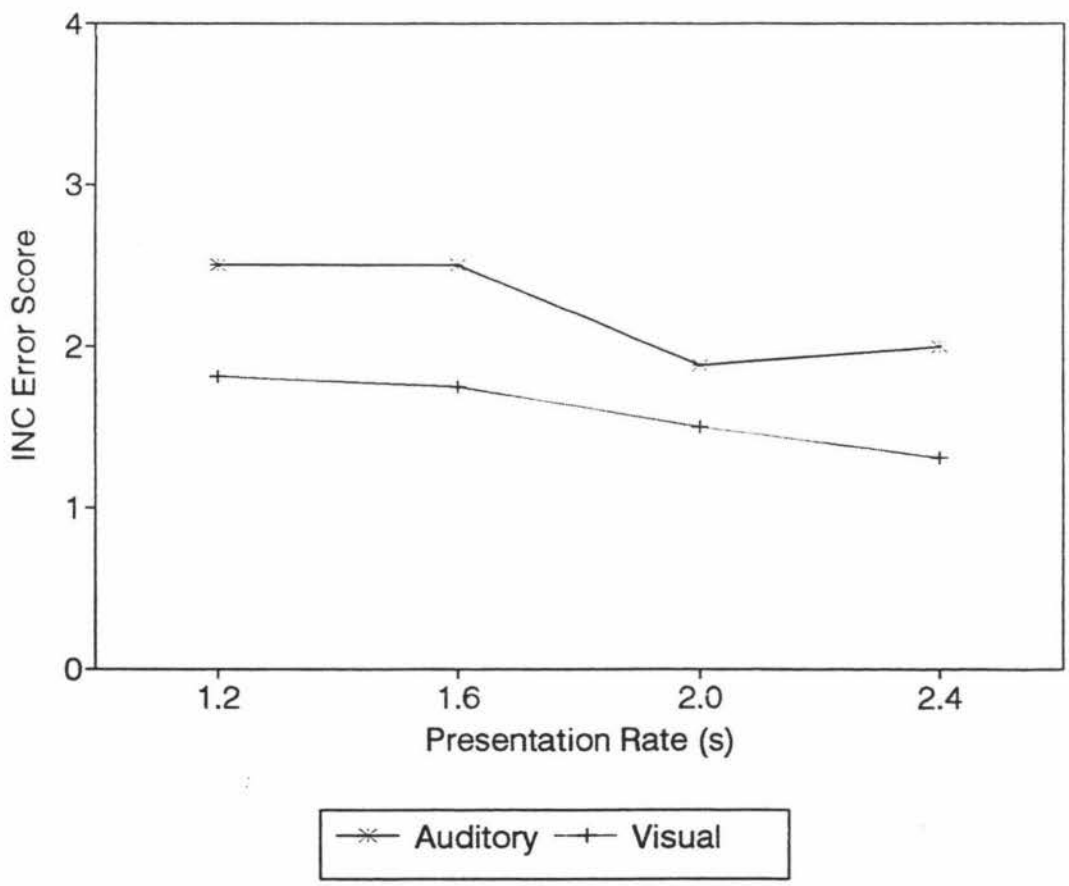

Figure 6. *Mean frequency of incorrect responses (INC) for all subjects in the auditory and visual stimulus presentation modalities as a function of presentation rate.*

The findings for the OM error type tended to mirror the pattern found for CI responses. The analysis of the mean frequencies for omissions revealed significant main effects for Mode, F (1,15) = 24.67, $p < .001$, $\eta^2 = .62$, and Rate, F (3,45) = 100.79, $p < .001$, $\eta^2 = .87$ (Appendix 12D). As Figure 7 shows, the mean frequency of omissions was higher at all presentation rates in the auditory mode than in the visual mode, and for both the auditory and visual modes the frequency of omissions increased with shorter ISIs. The absence of a significant Mode x Rate interaction effect, F (3,45) = 2.31, $p = .09$, $\eta^2 = .13$, indicated that the effect for presentation rate was reasonably stable across stimulus presentation modality, although η^2 shows that 13% of the variance was due to this interaction.

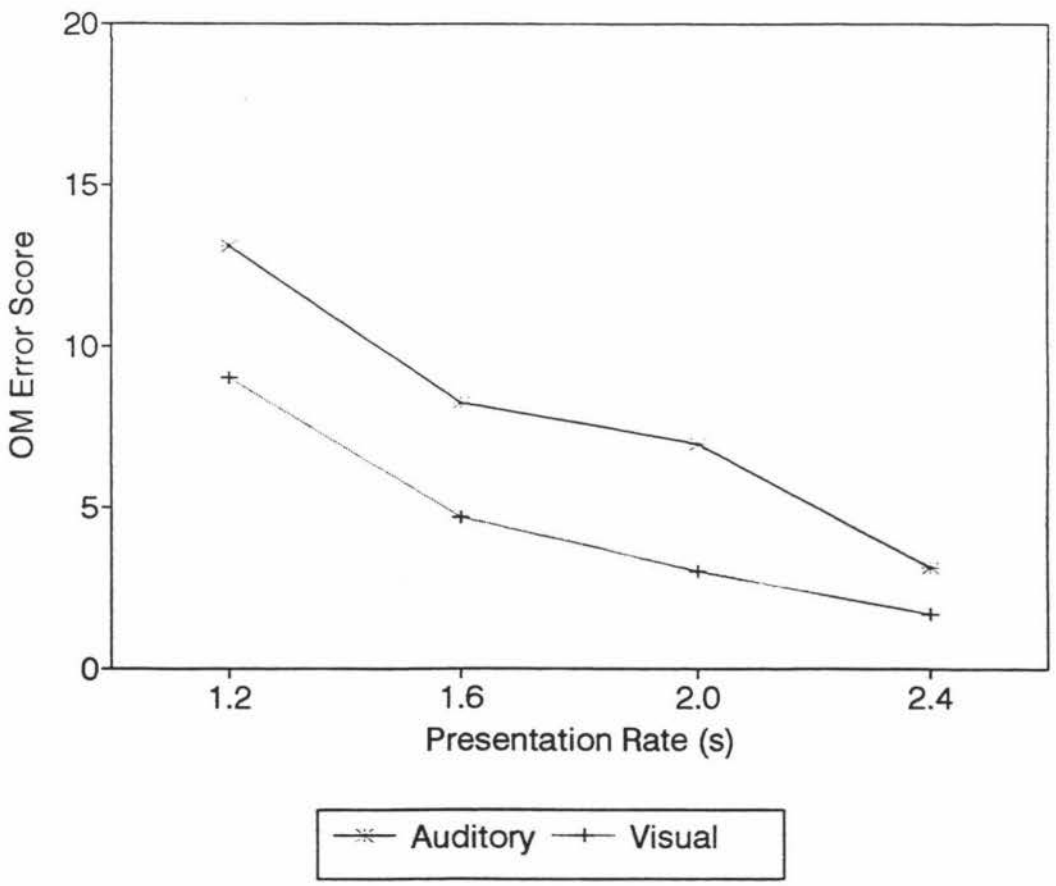

Figure 7. ***Mean frequency of omissions (OM) for all subjects in the auditory and visual stimulus presentation modalities as a function of presentation rate.***

Figure 8 presents the data from Figures 5, 6, and 7 combined, and illustrates the predicted effect of a disproportionate increase in the frequency of omissions over the other error types at faster presentation rates.

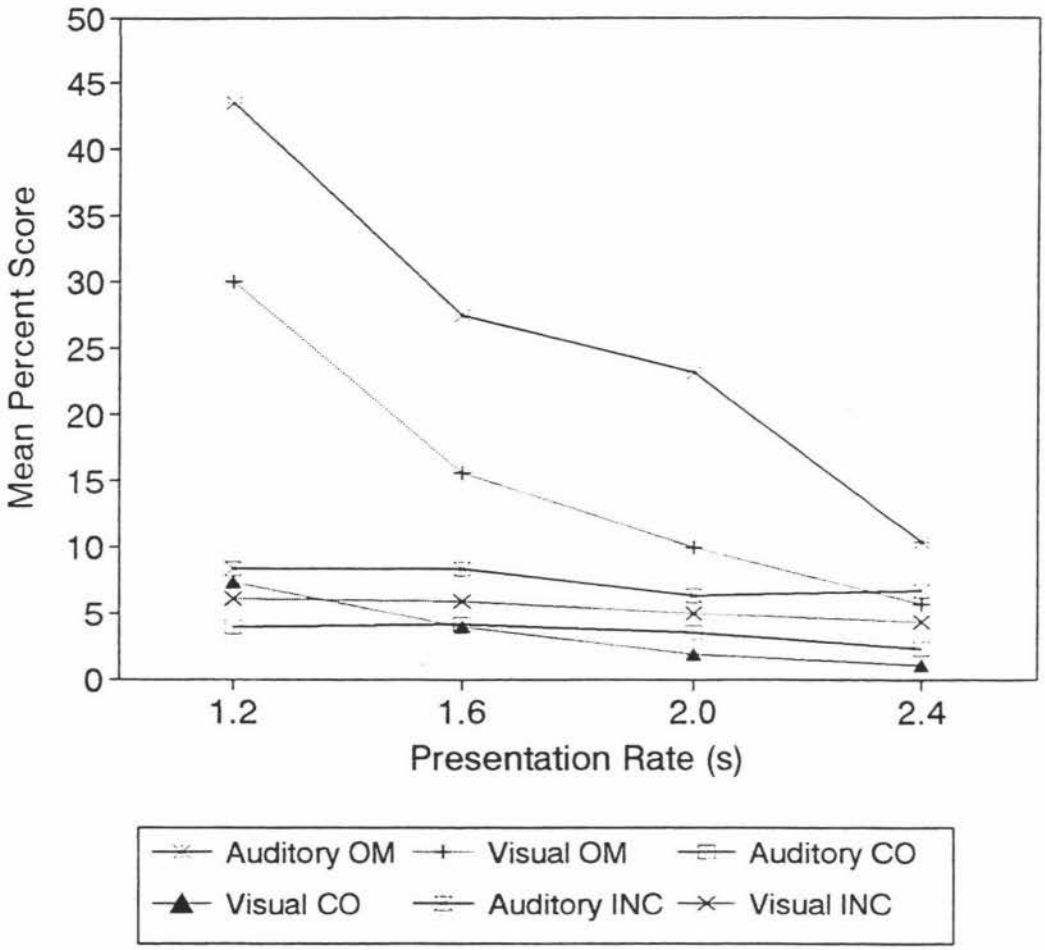

Figure 8. *Mean percentage of numerically correct responses falling outside the ISI (CO), numerically incorrect responses (INC), and omissions (OM) for all subjects in the auditory and visual stimulus presentation modalities as a function of presentation rate.*

A 2 x 4 x 3 (Mode x Rate x Error Type) within-subjects MANOVA (Appendix 12E) revealed significant main effects for both Rate, $F\,(3,45) = 92.50, p < .001, \eta^2 = .86$, and Mode, $F\,(1,15) = 47.19, p < .001, \eta^2 = .76$, in the absence of a Mode x Rate

interaction effect, $F\,(3,45) = 0.98, p > .05$. The finding for Mode reflects the overall trend toward a higher mean frequency of all errors in the auditory mode. The significant main effect found for Error Type, $F\,(2,30) = 32.37, p < .001, \eta^2 = .68$, indicates that the relative frequencies of the different types of errors are, on average, unequal. The Rate x Error Type, $F\,(6,90) = 38.10, p < .001, \eta^2 = .72$, interaction effect reflects the disproportionate rise in the frequency of omissions relative to other error types (see Figure 8).

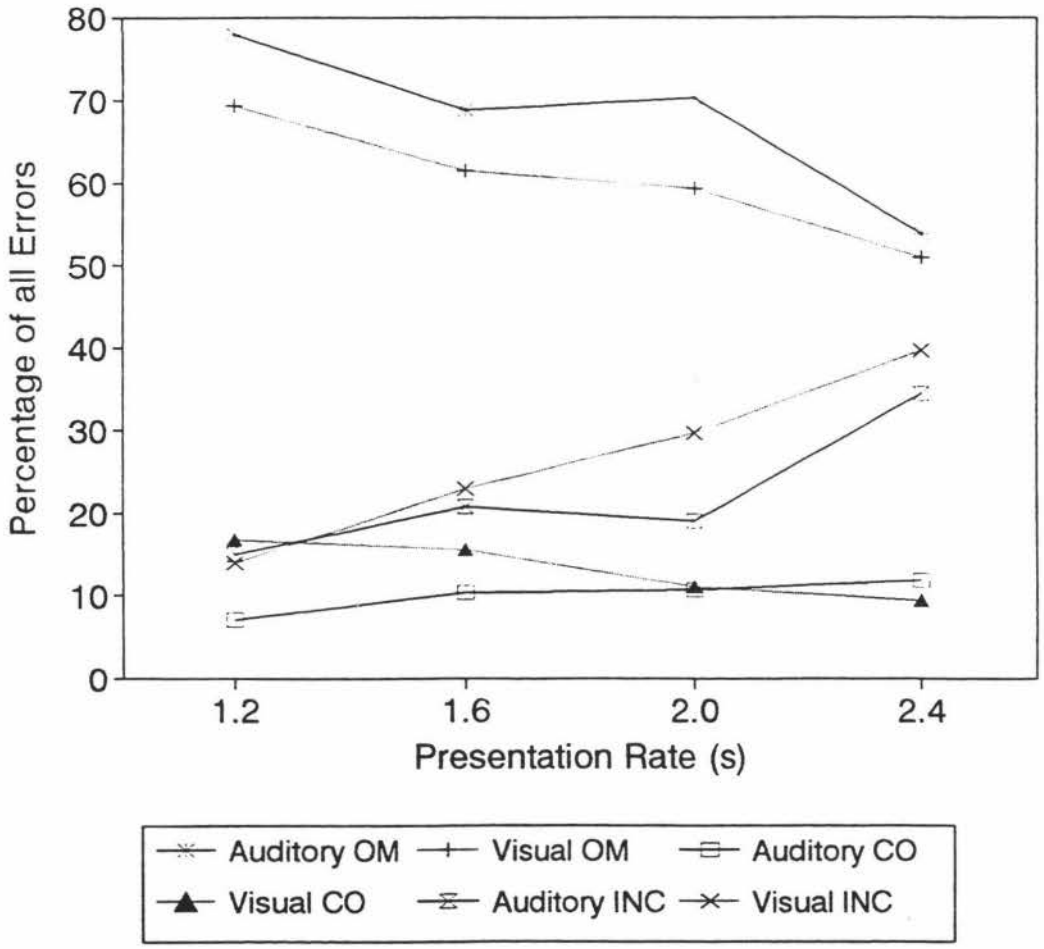

Figure 9. ***Mean percentage of numerically correct responses falling outside the ISI (CO), numerically incorrect responses (INC), and of omissions (OM) as a percentage of all errors for all subjects in the auditory and visual stimulus presentation modalities as a function of presentation rate.***

Further interaction effects for Mode x Error Type, $F(2,30) = 13.42$, $p < .001$, $\eta^2 = .47$, and Mode x Rate x Error Type, $F(6,90) = 2.57$, $p < .05$, $\eta^2 = .15$, are more clearly illustrated in Figure 9, which shows the mean frequencies of each Error Type as a percentage of all errors in the auditory and visual conditions across presentation rates. As Figure 9 shows, the proportion of OM errors is consistently greater for the auditory condition, whereas this pattern is, for the most part, reversed for the CO and INC error types, giving rise to the Mode x Error Type interaction. For both the CO and INC error types, however, the trend toward a greater relative proportion of errors in the visual mode is reversed for at least one presentation rate, at 2.4 s for CO errors and at 1.2 s for INC errors, contributing to the Mode x Rate x Error Type interaction.

CI scores by Task Duration

Table 3. *Mean frequencies (M) and standard deviations (s.d.) of correct responses falling within the response interval (CI) for all subjects for the three successive blocks of 10 digit pairs collapsed across presentation rate.*

	Block					
	1		2		3	
Mode	M	s.d.	M	s.d.	M	s.d.
Auditory	7.36	1.74	6.00	1.74	5.49	1.70
Visual	8.20	1.93	7.67	1.69	6.89	1.68

For the analysis of the effect of task duration on CI scores, the 30 response opportunities for each trial were divided into three successive blocks of 10 digit pairs. Table 3 (p. 66) gives the mean CI scores for each Block as a function of the modality of stimulus presentation collapsed across presentation rate. Figure 10 illustrates these means, and shows that the frequency of CI scores did decrease as a function of task duration in both the auditory and visual modes.

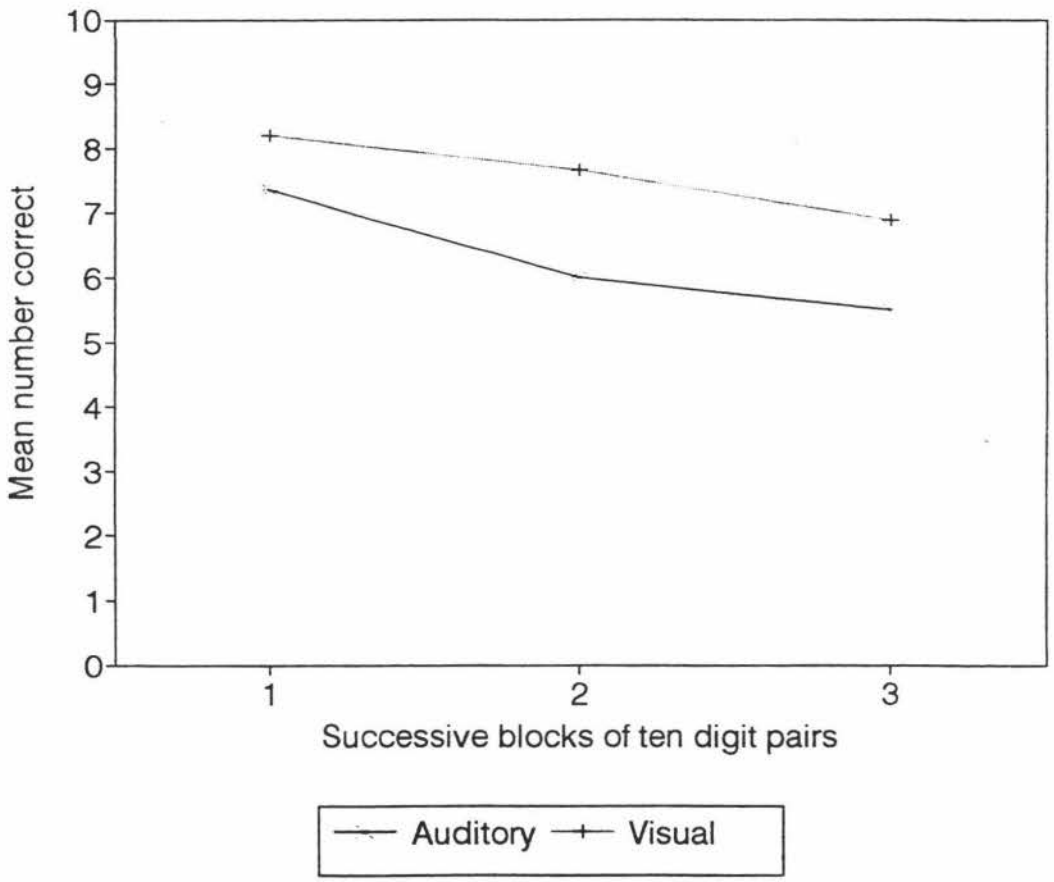

Figure 10. *Mean frequency of correct responses falling within the response interval (CI) for all subjects in the auditory and visual stimulus presentation modalities, collapsed across presentation rate, as a function of successive blocks of 10 digit pairs.*

The rate of decrease appears to have been slightly more pronounced in the audito mode. A 2 x 4 x 3 (Mode x Rate x Block) within-subjects MANOVA (Appendix 12F)

confirmed these trends, revealing significant main effects for Mode, $F\,(1,15) = 47.73$, $p < .001$, $\eta^2 = .76$, and Block, $F\,(2,30) = 25.84$, $p < .001$, $\eta^2 = .63$, and a smaller but significant Mode x Block interaction effect, $F\,(2,30) = 4.37$, $p < .02$, $\eta^2 = .23$. The significant main effect for Rate, $F\,(3,45) = 93.14$, $p < .001$, $\eta^2 = .86$, reflects the above findings for lower CI scores at shorter ISIs. A near significant Rate x Block interaction effect, $F\,(6,90) = 2.09$, $p = .06$, $\eta^2 = .12$, although not able to be seen in the collapsed data, is indicative of a small trend toward a more rapid decrement in scores as a function of task duration at the faster presentation rates.

CI Scores by Sex

Table 4. *Mean frequencies (M) and standard deviations (s.d.) for correct responses falling within the response interval (CI) for male and female subjects as a function of the mode and rate of stimulus presentation.*

		Presentation Rate							
		1.2		1.6		2.0		2.4	
Sex	Mode	M	s.d.	M	s.d.	M	s.d.	M	s.d.
Male	Auditory	14.38	3.38	20.50	3.46	21.88	3.76	25.50	1.41
	Visual	19.38	6.35	23.00	4.31	26.38	2.50	28.63	1.19
Female	Auditory	12.13	4.58	15.50	3.78	18.38	4.17	22.88	3.44
	Visual	14.63	3.89	21.75	6.30	23.50	4.14	24.75	2.87

As part of the replication of the Caroselli et al. (personal communication, 1994) study, an analysis of CI scores by Sex was conducted. The mean CI scores for males and females from Table 4 (p. 68) were submitted to a mixed 2 x 4 x 2 (Mode x Rate x Sex) MANOVA (Appendix 12G). Mode and Rate were the within-subject factors and Sex was the between-group factor. The analysis revealed a significant main effect for Sex, $F\,(1,14) = 4.87$, $p < .05$, $\eta^2 = .26$. As Figure 11 shows, CI scores for males were higher than those for females in every stimulus modality and presentation rate condition.

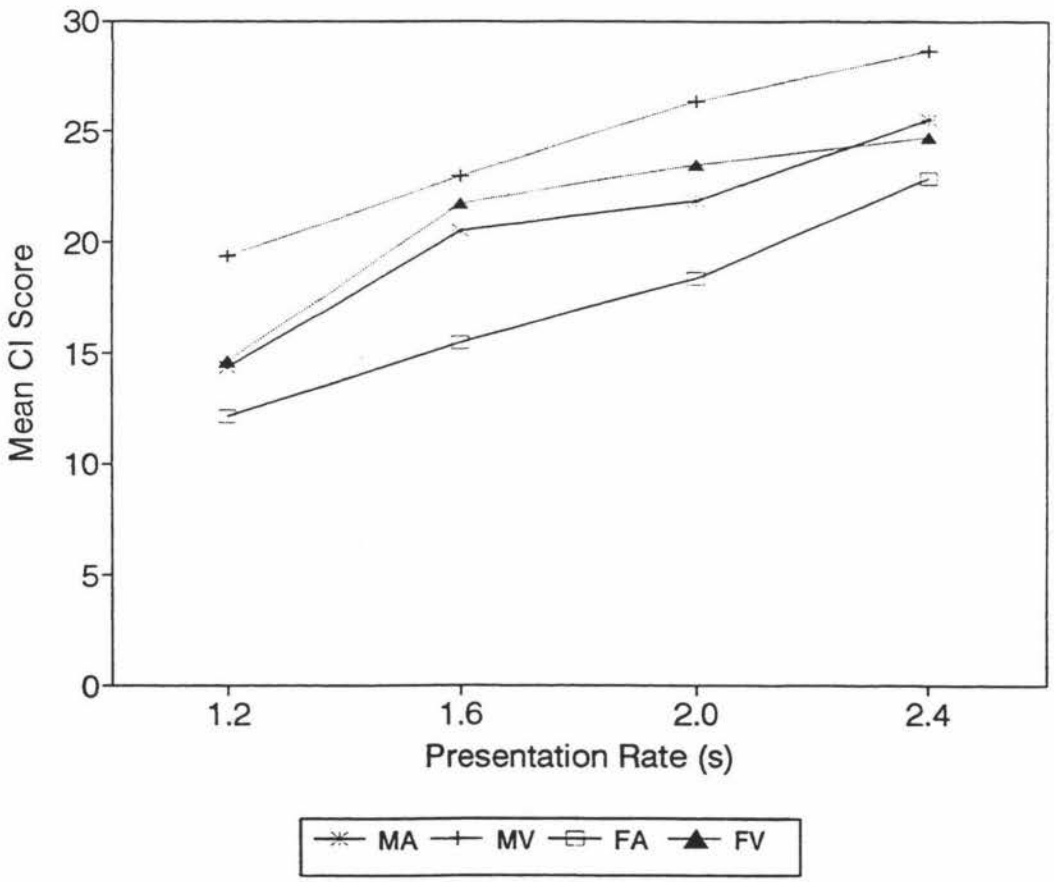

Figure 11. *Mean frequency of correct responses falling within the response interval (CI) for male (M) and female (F) subjects in the auditory (A) and visual (V) stimulus presentation modalities as a function of presentation rate.*

The significant main effects for Mode, $F\,(1,14) = 44.10$, $p < .001$, $\eta^2 = .76$, and Rate, $F\,(3,42) = 86.52$, $p < .001$, $\eta^2 = .86$, and the absence of significant interaction effects indicated that the observation of higher CI scores for males was stable across stimulus modality and presentation rate.

Discussion

The first hypothesis for Experiment 1 was that, at equivalent rates of stimulus presentation, paced serial addition performance in the visual modality of stimulus presentation would be superior to that found for the auditory modality. The results of the comparison of CI scores as a function of presentation rate are clearly consistent with this hypothesis.

Furthermore, the attention given to methodological issues in the present study may have enabled a clarification of the findings of Caroselli et al. (personal communication, 1994). The inconsistencies in the relationship between CI scores on the auditory and visual tasks in that study were not found in the present study, which suggests that the stimulus modality effect is more robust than might have been thought. This is further indicated in the finding of a greater magnitude of superiority for the visual task than was observed by Caroselli et al.

Although the results of the current investigation are consistent with and clarify the findings of previous research, they do not explain why it is that paced serial addition performance is more accurate in the visual than in the auditory mode of stimulus

presentation. As noted earlier, Sampson and MacNeilage (1960) proposed that rescanning of the visual stimulus resulted in improved processing efficiency and superior performance. While this explanation might be applied to the present results, such an approach is inconsistent with the overwhelming evidence suggesting that performance changes for paced serial addition can be related almost directly to the influence of temporal factors such as stimulus duration, pacing rate, and task duration. It also represents a major departure from Sampson and MacNeilage's temporal integration theory, which maintains that attentional factors are at the root of variations in paced serial addition performance.

The speculations of Caroselli et al. (personal communication, 1994), to the effect that memory limitations or response interference may affect PASAT performance, are both plausible explanations of the stimulus modality effect. Furthermore, they are perhaps more consistent with current views that see the cognitive operations involved in PASAT performance as being dependent on attentional factors. However, explanations based on these premises also have the potential to neglect the importance of temporal factors. To be consistent with the existing findings and current views, any account of the stimulus modality effect should probably be based on the temporal and attentional elements of paced serial addition.

The elements necessary for such an explanation may be found by returning to the earlier review of theoretical accounts for paced serial addition findings. There it was noted that van Zommeren et al. (1984) saw PASAT performance as possibly being dependent on the division of attention inherent in the demands of the task, in that it

requires the subject simultaneously to attend to multiple processing elements. Using this theory, it might be hypothesised that superior performance in the visual stimulus modality relative to the auditory modality results from differences in the attentional demands imposed by each task. From this it could be inferred that, when the SD and ISI are equal, the auditory task somehow involves greater attentional demands than the visual task.

To explain how the attentional demands of the tasks might differ when variables such as SD and ISI are held constant, it can first be noted that Sampson and MacNeilage (1960) failed to consider an alternative to their rescanning explanation for the effects found for SD and stimulus modality. This alternative was that a visual stimulus, which is available for processing at virtually the instant of presentation, may be processed within a shorter time from onset than an auditory stimulus, the presentation of which is prolonged over a period of 250 - 450 ms. If, and it seems entirely plausible on a task requiring rapid responding to sequential stimuli, the subject begins the cognitive operations necessary to generate and deliver their response at the earliest point possible, then the earlier availability of the visual stimulus might result in an effective lengthening of the response interval.

In effect, this explanation contains both the temporal and attentional elements which would appear to be necessary in an attempt to account for the stimulus modality effect found for paced serial addition performance. The way in which it departs from earlier accounts is that it takes into consideration the possibility that the cognitive processes involved in the task may not correspond exactly to or be limited by the stimulus onset

and offset. Earlier accounts appear to assume that only the processing related to stimulus perception and encoding will take place during the SD, but it may be that other operations can begin prior to stimulus offset.

Indeed, this theory might also be extended to account for findings other than the stimulus modality effect. If it is assumed that an effective lengthening of the response interval lessens the attentional demands of the visual task relative to the auditory task, then it might also be the case that the performance change within each stimulus modality as a function of pacing rate occurs for the same reason. As the stimuli are presented closer together in time, the subject has less time to perform the same cognitive operations, and the attentional demands of the task become greater.

Unfortunately, while the results of Experiment 1 as they relate to the first hypothesis appear to be consistent with the explanation just described, which for convenience will be called the divided attention theory, they can not be seen as a test of the theory. Further research is required to assess the idea that the effectively longer response interval in the visual modality is a crucial factor underlying the modality differences found in Experiment 1.

The second hypothesis stated that even though visual stimulus presentation results in superior performance at equivalent presentation rates, performance in both the auditory and visual modes of stimulus presentation is a function of the same underlying form of information processing. On the basis of this hypothesis, a comparison of the CI scores across stimulus modalities was expected to show similar patterns of responding as a

function of presentation rate. The results clearly illustrate that the pattern of CI scores as a function of presentation rate was indeed similar for the auditory and visual modes. Again, all that can be said is that this result is consistent with the hypothesis tested. There is nothing in the present data to suggest that the underlying cognitive processes in the auditory and visual tasks are fundamentally different.

As part of the planned extension of the findings by Caroselli et al. (personal communication, 1994) the present investigation predicted, on the basis of findings by Sampson and MacNeilage (1960) and Gronwall and Sampson (1974), that CI scores would decrease as a function of task duration and that a similar trend would emerge for both the auditory and visual stimulus presentation modalities. The expected decrease in CI scores did occur, and this effect appeared to be constant across stimulus presentation modalities despite the superiority of performance in the visual modality. This result is again consistent with the hypothesis that similar cognitive processes underlie paced serial addition performance in both the auditory and visual modes of stimulus presentation.

While the findings for analyses involving CI scores are consistent with the respective hypotheses so far discussed, the findings for error types are not so clear cut. In the case of omissions, which tended to make up a high proportion of all errors, the pattern across presentation rates and between modes generally mirrored the findings for CI scores, and are consistent with the predictions derived from the second hypothesis. The patterns for CO and INC errors, both of which occurred at fairly low frequencies, were more complex and appeared sometimes to contradict the idea of similar cognitive processes underlying the two modalities.

The pattern of CO errors suggest that they occurred at a lower frequency in the visual mode at longer interstimulus intervals, but that this trend was reversed at the fastest presentation rate. This finding might relate to the way in which the subjects responded to their subjective impressions of the relative difficulty of the auditory and visual tasks. If the subjects experienced the auditory task as being harder, and both the findings and the comments given by some subjects suggest that this was so, it is possible that as the presentation rate became faster subjects became less likely to attempt a response that they were not sure was correct. In the visual mode, subjects may have continued to attempt to respond, with the consequence that they were more likely to give the correct response outside the interval.

At the slower presentation rates, where neither the auditory nor the visual task was experienced as particularly difficult, the lower frequency of CO errors in the visual mode may simply reflect the overall tendency for more accurate responding on the visual task. If this were true, it would mean that in the auditory mode the frequency of omissions should increase more rapidly with faster presentation rates than in the visual mode, as some potentially correct responses are being omitted. Such a trend can be observed in Figure 4. It is possible, therefore, that the unexpected pattern found for CO errors is due to a motivational factor rather than to a difference in the processing that underlies performance in the stimulus presentation modalities.

In effect, this interaction of Mode and Rate would point to a methodological confound in the present study, induced by having subjects perform tasks that involved the same cognitive processes but which occupied different levels of subjective difficulty.

It is also possible that the low frequency and relatively high variability of CO errors (see Table 2) makes this an unstable index of paced serial addition performance. The same may also be true of the INC error category.

In the case of INC errors, the predicted increase in frequency at faster presentation rates did occur, but not at a statistically significant level, making this the only response type that did not vary with changes in presentation rate. This may have been due to the instability of this index, as the frequency of INC errors was low. However, the frequency of INC errors was, in fact, higher on average than of CO errors, for which the expected main effect for Rate was found. The possibility that remains is that faster rates of stimulus presentation do not cause the frequency of INC errors to increase. Given that the divided attention theory provided a plausible and fairly parsimonious account for the stimulus modality effect, it was decided to return to Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) general theory of controlled and automatic information processing in search of a possible explanation for this unexpected finding.

Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) general theory of information processing is a two-process theory. Their theory maintains that normal human information processing is of two general types - automatic and controlled. Automatic processing is that which, once activated, proceeds "...without subject control, without stressing the capacity limitations of the system, and without necessarily demanding attention" (Schneider & Shiffrin, 1977, p. 1). They further maintained that controlled processing "...requires attention, is capacity limited (usually serial in nature),

and is controlled by the subject" (p. 1).

According to the theory, divided-attention deficits, which are one class of selective-attention deficits, occur when a task demands that controlled processing is directed at additional sensory inputs or memory elements. As this form of processing is said to be capacity-limited and serial, a level of additional demands that exceeds that capacity or requires simultaneous processing causes an information overload. This results in reduced processing efficiency, and consequently, a decrement in performance. This part of Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory, therefore, was the basis for the divided attention theory described earlier.

The other element of Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory describes a quite different form of information processing, namely that having an automatic nature. The authors maintain that this automatic processing may require controlled initiation, but that once it is initiated it will run automatically to completion. Furthermore, these automatic processes are said not to be hindered by the capacity limitations of short term memory store that are caused by high levels of attentional demands. This distinction between automatic and controlled information processing gives rise to an interesting possibility in relation to the results of the present research.

Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory might predict that any aspect of the information processing involved in paced serial addition performance that operated in the nature of automatic processing would not be affected by manipulations that increase the attentional demands of the task. If it was assumed that

the processing involved in arriving at a numerically correct addition for each digit pairing on the paced serial addition task was a function of automatic processing, then it might be predicted that the frequency of numerically incorrect responses would not increase as a function of presentation rate. This finding for Experiment 1 would therefore appear to be consistent with a view of mental addition as an example of automatic processing. To understand how this might be so, a closer look at what is involved in the mental addition required in paced serial addition is necessary.

The additions called for on the paced serial addition task are essentially quite simple manipulations of pairs of single digit numbers. These are additions that would presumably be performed at a very low error rate in everyday situations, and might constitute what Shiffrin and Schneider (1977; Schneider & Shiffrin, 1977) describe as examples of an over-learned skill. It is these over-learned skills that they believe are functions of automatic information processing. It may be that the increased attentional demands imposed by accelerated pacing actually do little to disrupt such automatic processing. If, therefore, the mechanism underlying INC errors is a relatively infrequent fault in the automatic addition of numbers, and one which is not exacerbated by increasing attentional demands, then this might explain why an increase in INC errors did not occur with faster pacing.

Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory, taken a step further, might be used as a basis for speculation as to what particular aspect of the information processing underlying paced serial addition performance might be disrupted by the increased attentional demands associated with faster rates of stimulus

presentation. A possible clue to this lies in the finding that the decrement in accuracy largely reflects an increase in the number of omissions. This finding seems to indicate that lowered performance does not occur because subjects give more incorrect responses, but rather that it occurs by default, in that correct responses become less frequent. If it is assumed that this is due to divided attention deficits in controlled processing, and that these deficits do not affect the actual operations involved in the mental additions, then it may be that the mental additions required simply do not take place. This proposal is consistent with Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory, in that they maintain that automatic processes may require controlled initiation.

Assuming that the element of controlled paced serial addition processing that may be disrupted by increased attentional demands is the point at which the mental addition is initiated, it is possible to predict the pattern of results that should emerge as a function of presentation rate. At slow presentation rates, where the attentional demands are low, the frequency of CI responses will be high and the frequency of all errors will be low. As the speed of stimulus presentation becomes faster and the attentional demands increase, the likelihood that the controlled initiation of the mental addition will be interfered with will also increase. The result of this will be a greater frequency of omission errors and a consequent decrement in accuracy. However, when the initiation is successful, the response given will tend to be numerically correct, even though the likelihood that it will fall outside the response interval may increase, The upshot of this is that the frequency of INC errors will not rise dramatically.

Of course, these proposals are purely speculative, but the fact remains that Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory appears to be well suited to explaining the results of the analyses conducted for Experiment 1. It seems that further investigation of the divided attention approach to paced serial addition performance is warranted.

A somewhat unexpected finding for Experiment 1 was that CI scores for males were higher than those for females in all Mode x Rate conditions. This effect is supported by only one other finding in the literature, that of Brittain et al. (1991). Although the effect found in that study reached a fairly high level of significance ($p = .013$), the authors attributed it to the statistical power of the analysis and dismissed the finding as being of "minimal practical significance" (p. 169).

The actual magnitude of the sex difference observed in the study by Brittain et al. (1991) is difficult to gauge as the authors give only the mean difference in seconds per correct response (SCR) between all male and female subjects at each of the four presentation rates. However, by extrapolating from some of their results, a rough estimate can be calculated for one of their subject groups. The group which was probably most comparable to the subjects in the present study was made up of 49 male and female subjects who were under 25 years of age and who were assessed as having IQs greater than 109. The mean SCR for that group was 2.90. Using the conversion tables included in the Appendix to the Brittain et al. study this can be translated into a mean number of correct responses of just over 40 (out of 49), or around 82%. The mean difference between all male and female subjects at the 2.4 s presentation rate was

0.31 SCR. The score range corresponding to .31 SCR is approximately 38 to 43 correct responses, which, when applied to the group in question, gives a difference between males and females of about five correct responses (77.5 % - 87.8%). For the present study, the mean CI score on the auditory task at the 2.4 s rate was 25.5 (85%) for males and 22.88 (76.3%) for females. This difference of 8.7% between males and females compares well with the estimated difference in the Brittain et al. study of 10.3%.

For practical purposes, Brittain et al. (1991) may have been correct in attaching little importance to their finding, as it is likely that the great majority of people being administered the PASAT in clinical assessment are male. However, and it is indicative of the weakness of recent research concerning the PASAT, it is surprising that the authors failed to consider the theoretical importance of their results. In terms of understanding the cognitive processes that underlie PASAT performance, the possibility that there exist two distinct groups of normal subjects who might reliably differ in their performance is of great significance.

Although there appears to be evidence for the existence of a sex difference in the present study, explaining the difference may be more difficult that demonstrating it. Recent comprehensive reviews in the fields of attention and information processing (e.g., Kinchla, 1992; Massaro & Cowan, 1993) give no indication that sex differences are considered to be an important factor in either research or theory. In their review of group differences for selective and sustained attention tasks, Davies, Jones, and Taylor (1984) devote only a single paragraph to sex differences, and conclude that they are

non-existent among both children and adults.

It may be that the observed difference is related not to the attentional elements of the paced serial addition task, but more to the nature of the cognitive operations involved. When viewed from this perspective, the superior performance of males is consistent with the general findings for sex differences in cognitive functions. Lezak (1983) points out that findings of male superiority in mathematics and some spatial abilities are relatively common. Although this may be partly attributable to differences in the socialisation of males and females (see Richardson & Woolfolk, 1980, for a review), a growing number of influential theorists have ascribed such performance differences to fundamental organisational, functional, and sometimes structural differences in the brains of males and females (e.g., Geschwind & Galaburda, 1987; Hellige, 1993; Kimura, 1992; McGlone, 1980; Springer & Deutsch, 1993). Although there is by no means widespread agreement as to the cause of sex differences in cognitive functions, it appears that the findings of the present study are not inconsistent with the general findings for sex differences.

In summary of Experiment 1, the results obtained are consistent with the proposition that paced serial addition performance in the auditory and visual modes of stimulus presentation is a function of the same underlying cognitive processes, but that under the same conditions of pacing, performance in the visual modality is superior. The implication of these finding for clinical use of the instrument is that the visual version, which could be easier to administer and less stressful for subjects, may be capable of yielding similar information to the auditory form that is in conventional use. While this

may not be true for all subjects, such as those who are suffering a degree of photosensitivity consequent to recent concussion, the more recent use of the PASAT with other clinical groups and the increasing use of computers in clinical practice should make the visual task a viable alternative to the conventional PASAT.

The observation that INC errors appear to remain fairly constant across presentation rates has some potential to increase the utility of clinical testing with the PASAT. It may be that the test can be developed to investigate the possibility of deficits in automatic as well as in controlled information processing. A major implication of the present findings relates to the original norms for the PASAT, which were based on the results of research using only male subjects. Perhaps these norms are not valid for use in evaluating the performance of female subjects or patients.

The implications for research with the auditory and visual forms of paced serial addition are that modality-specific differences do exist and that these may interact with subjective and motivational factors to cause subtle variations in performance patterns across modality. The effect found for Sex suggests that this factor could prove to be a valuable point of comparison in future research, but the nature of possible processing differences between the sexes needs to be more comprehensively evaluated.

Perhaps the most important finding in terms of future research relates to the use of Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) general theory of controlled and automatic information processing to explain the results, as suggested by van Zommeren et al. (1984). This theory gives a plausible account of the present results,

and when combined with a consideration of the temporal nature of the task, appeared to contain the necessary elements for a sound explanation of a range of paced serial addition findings. Therefore, one aim of the second experiment was to further explore the value of Shiffrin and Schneider's theory for a better understanding of the cognitive processes underlying paced serial addition performance.

EXPERIMENT 2

In Experiment 1 the study by Caroselli et al. (personal communication, 1994) was replicated, and their findings clarified and extended. It was found that the results were most adequately interpreted in terms of Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) general theory of controlled and automatic information processing. This theory maintains that a high level of demands on a task which requires the subject to attend to multiple stimuli and information processing operations will cause divided attention deficits in controlled processing. The pattern of results found in Experiment 1 suggested that the controlled processing disrupted by the attentional demands of paced serial addition might be at the point at which the mental addition of the stimulus numbers require initiation. These proposals are entirely speculative, however, as Experiment 1 was not a test of the divided attention theory.

It was decided, therefore, to conduct Experiment 2 as a test of the divided attention theory for paced serial addition. Difficulties immediately arose, however, in respect of the design of such a test. As noted earlier, the PASAT is a quite different task to those normally used in research into attention, and the information processing involved is more complex than that usually investigated. For example, in Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) studies the subjects were required to detect a target within an array made up of target and foils, and the attentional load was varied by having the subjects memorise different numbers of targets. On the PASAT, the information required to be held in memory is constantly changing, and the operations necessary to attend to and encode stimuli, perform mental additions, and respond, are

complex. In addition, these operations must be coordinated and performed in a sequential manner. Furthermore, perhaps the most logical way of varying the attentional load of the PASAT would be to change the rate of stimulus presentation, and this is already an integral part of the test.

Consequently, Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory, though it gives an appealing account of the information processing underlying PASAT performance, does not offer a straightforward approach to testing the divided attention theory for paced serial addition. The following section examines the divided attention research literature with the aim of isolating a different approach to testing the divided attention hypothesis.

Divided Attention Research

One approach often used in the study of attention deficits, and which might be used as an heuristic device in conceptualising and studying the PASAT, is the dual-task paradigm (Navon & Gopher, 1979). The focus of this approach is on how task performance varies as a function of whether the task is performed alone or simultaneously with another task. The tasks used can be various combinations of sensory, cognitive, and motor performance. One example of this is the dichotic listening approach, where subjects are required to attend simultaneously to two concurrent speech messages (Allport, Antonis, & Reynolds, 1972). Often, subjects are required to perform a cognitive task, such as sentence repetition, simultaneously with a motor task, such as balancing a dowel on their finger (Freidman & Polson, 1981).

The findings in dual-task research are complex and a wide range of theories have been proposed to explain them (Navon & Gopher, 1979). In general, it is found that most tasks can be performed better alone than when done simultaneously with another, but there are many examples in which simultaneous performance does not affect, or even seems to enhance, sole performance. Navon and Gopher point out a range of factors, such as the additivity of demands, the independence of tasks, and the controllability of resources, that they believe are important determinants of dual-task performance.

In essence, then, the rationale behind the dual-task approach is that it can be used to manipulate attentional demands and create a division of attention between tasks. This immediately suggests that the same could be done with the PASAT. Such an approach was used by Gronwall and Sampson (1974) when they demonstrated that simultaneous performance on the PASAT and a continuous reaction-time task had a detrimental effect on PASAT scores. Their finding is consistent with the proposal that errors on the PASAT can result from the division of attention between tasks. However, the question of interest here is whether different levels of divided attention *within* the paced serial addition task as a function of presentation rate are responsible for the decrement in performance across rates.

Nonetheless, the dual-task approach appeared to be an interesting and informative way of conceptualising the PASAT, in that the elements of PASAT performance might be thought of as sub-tasks within the overall task. To clarify this conceptualisation, Figure 12 depicts a hypothetical representation of the processing involved in paced serial

addition performance. The processing elements are those suggested by van Zommeren et al. (1984, p. 88).

Stimulus	Processing	Response
n	Perception of stimulus n Encoding of stimulus n Maintenance of stimulus n in memory	
$n + 1$	Perception of stimulus $n + 1$ Encoding of stimulus $n + 1$ Retrieval of stimulus n from memory Mental addition of stimuli n and $n + 1$ Generation and articulation of response n Maintenance of stimulus $n + 1$ in memory	n
$n + 2$	Perception of stimulus $n + 2$ Encoding of stimulus $n + 2$ Retrieval of stimulus n from memory Mental addition of stimuli n and $n + 2$ Generation and articulation of response n Maintenance of stimulus $n + 2$ in memory	$n + 1$

Figure 12. *A hypothetical representation of the processing elements relating to stimuli, memory, mental transformations, and responding for paced serial addition.*

As Figure 12 shows, the different forms and stages of processing that might be said to underlie a single paced serial addition response, even in a comparatively simple conceptualisation, are many and complex. Following the presentation and encoding of stimulus $n + 1$, the subject must retrieve stimulus n from memory, perform the mental operations necessary to arrive at their sum, and then generate and articulate their response. Simultaneously, the subject has to perform the operations necessary to

maintain the identity of stimulus $n + 1$ in memory, so that it may be retrieved when stimulus $n + 2$ has been presented and encoded.

The information processing and cognitive operations involved in the PASAT appear more complex than would normally be addressed in a simple dual-task experiment. In fact, as the PASAT involves sensory, cognitive, and motor performance, it might be said to consist of at least three major sub-tasks. At least some of these tasks, such as maintaining the identity of a stimulus in memory while attending to another stimulus, must overlap within the PASAT, even at slow rates of presentation. This might explain why errors occur, albeit at a low level, even at speeds at which the PASAT is relatively easy to perform. Faster presentation rates must increase this overlap, and perhaps cause some operations that were performed "alone" at slower rates to overlap with others, resulting in an increased division of attention. Hence, accuracy declines.

Such a conceptualisation, with its multitude of "sub-tasks", however, defies simple analysis. What is required is a more manageable conceptualisation in terms of a dual-task dichotomy. Using the hypothetical representation in Figure 12, it is comparatively easy to derive such a dichotomy by focusing on stimuli and responses, which between them represent the independent and dependent variables. The first task might be thought of as consisting of stimulus-related processes. These would include the perception, encoding, and memory operations performed on stimuli. At some point, the processing involved becomes more response related. This second task includes operations such as the retrieval and mental addition of digits, and the transformation of the product into motor output in the form of the response. Although the division between stimulus- and

response-oriented tasks is quite arbitrary, this conceptual dichotomy achieves a coarse representation of the behaviours that might be seen to occupy opposite poles on the continuum of behaviours that make up paced serial addition performance.

What is important in this conceptualisation is that the sub-tasks proposed must necessarily be serial in nature, in that the response sub-task n, for example, is dependent on the successful completion of the stimulus sub-task $n + 1$. Each sub-task can be said to demand the allocation of attentional resources. Thus, it can be assumed that as the temporal spacing between stimuli is reduced sub-tasks which are normally performed serially are forced toward contiguity or overlap, and the ability to divide attention between the sub-tasks is compromised. Such a compression of the temporal parameters of processing is, of course, inherent in the PASAT as a function of presentation rate.

Given the serial nature of the PASAT, another temporal division of attention must exist between each response and the following stimulus. In this case the performance of the stimulus sub-task is not dependent on the success or accuracy of the preceding response sub-task, as the response, once given, is redundant. It should therefore be possible for response sub-task n and stimulus sub-task $n + 2$, for example, to take place simultaneously, but with a greater load on attention than if they took place consecutively. Again, a progression from serial to simultaneous processing demands for the dual sub-tasks is inherent in the PASAT.

Although the dual-task approach provides a rational way of thinking about how divisions of attention might operate within the PASAT, it is not the only way of

conceptualising the divided attention hypothesis. Another approach is the theory proposed by Friedman and Polson (1981; Friedman, Polson, Dafoe, & Gaskill, 1982) generated in part to account for inconsistencies found in dual-task research.

Friedman and Polson (1981; Friedman et al., 1982) developed a limited-capacity information processing theory within the context of hemispheric differences in performance. According to these authors (Freidman & Polson, 1981), the findings from the divided-attention and dual-task literatures, which were usually accounted for in terms of single-capacity or selective activation models, can be most parsimoniously accounted for by a theory postulating that the left and right cerebral hemispheres represent independent information processing resource systems.

Based on concepts such as inhibition, facilitation, and hemispheric specialisation of function, Friedman and Polson's (1981; Friedman et al., 1982) theory maintains that the usual pattern of dual task performance results when two tasks competed for the limited processing resources of a single hemisphere. An example of this is when the ability of a right-handed subject to balance a dowel with their right hand is reduced or inhibited by the concurrent performance of a sentence repetition task. As both tasks are assumed to be functionally lateralised to the left cerebral hemisphere (Friedman & Polson, 1981), competition for attentional resources occurs. Consequently, dowel balancing performance is worse in the dual task condition.

Freidman and Polson (1981) also note, however, that the same combination of tasks actually enhances dowel balancing for the left hand relative to when the balancing task

is performed alone. According to their theory, this occurs because the demands of the sentence repetition task, performed in the left hemisphere, cause an overall increase in resource allocation in the brain. Therefore, relatively greater resources are also available in the right hemisphere for simultaneous dowel balancing than are present for this task when performed alone. As there is no direct competition for these resources, because each task is in the main being performed by one hemisphere, dowel balancing for the left hand improves.

Freidman and Polson (1981) reviewed a number of studies in which the lateralisation factor related not only to which hemisphere was assumed to be specialised for a task but also to which hemisphere received the stimulus information. One of these studies (Hellige & Cox, 1976) involved subjects having to hold in memory either a list of nouns or a pattern of dots, while simultaneously having to name additional nouns that were presented to the left or right hemisphere of their brain. As a dual-task (according to Friedman & Polson, 1981) experiment, this example is not unlike the PASAT, in that it contains sensory, cognitive, and motor elements.

One of Hellige and Cox's (1976) findings was that when stimuli were directed to the same hemisphere that was assumed to be specialised for the type of information being maintained in memory (left hemisphere for nouns and right hemisphere for dots), a performance decrement in noun naming resulted. According to Friedman and Polson (1981), this decrement occurred because lateralised presentation of the stimuli varied the division of attention from between hemispheres to within a single hemisphere. In the latter case, processing resources became overloaded by the overlap between competing

tasks, and performance declined.

Returning to the PASAT, the logic of the dual-task conceptualisation can now be appreciated. In the discussion of the results of Experiment 1, a division of attention was assumed to exist within the PASAT, and the increase in attentional demands associated with faster presentation rates was said to be the cause of increased errors. By employing the strategy of lateralised stimulus presentation, however, this assumed division of attention can become a functional division of attention operating between and within the cerebral hemispheres of the brain. The point of such an exercise is to functionally separate the new input from the hemisphere which is engaged in processing the answer to the last sum. It should therefore be possible to evaluate the effect on responses of different attentional loads within each hemisphere as a function of stimulus lateralisation.

Implicit in this approach is the assumption that certain elements of processing occur in only one hemisphere. For example, Hellige and Cox (1976) assume that memory operations take place in the hemisphere that is specialised for the type of stimuli involved. In the case of the PASAT, it is necessary to specify which hemisphere is engaged in processing the answer to the last sum. Given that numerous cognitive operations are involved in the response task, it is not possible to state whether it is wholly, or even partly, functionally lateralised in one hemisphere. However, a considerable body of research indicates that the language and motor elements of this task must be left hemisphere functions in the majority of right-handed subjects (Hellige, 1993). Therefore, if this element of the response task is assumed to be constant, it

should be possible to evaluate changes in performance depending on which hemisphere the stimuli are presented or directed to.

Given the complexity and serial nature of the PASAT, however, it is necessary to specify the point at which the stimulus-response relationship should be measured. According to Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory, DADs occur when controlled processing must be directed at additional sensory or memory elements. Returning to Figure 12, we see that the greatest possible attentional load in the form of memory and sensory elements for response n is present in the additive effects of the processing that must occur between the presentation of stimulus n and response n. This approach, however, ignores the fact that another stimulus, $n + 1$, has also been presented during this interval, so a second approach is required.

This second approach, which takes into account the fact that each response is related to two consecutive stimuli, is to evaluate performance changes indexed by response n according to which hemisphere, or hemispheres, both stimulus n and stimulus $n + 1$ were directed to. This is a more complicated approach, as it gives rise to four possible combinations of left and right hemisphere stimulus presentation. As the following discussion shows, however, it may not be necessary to consider all of these possible conditions in the analysis.

In summary, it was decided that a useful and interesting way of investigating the divided attention hypothesis would be to present the paced serial addition stimuli in a

lateralised fashion. Such an approach allowed for a test of two opposing theories of attention: the independent resource theory of Friedman and Polson (1981; Friedman et al., 1982), and the selective activation theory of Kinsbourne (1975).

Theories and Hypotheses

It was argued earlier that treating the PASAT as being inherently a dual task would allow a test of the divided attention theory with the aim being to gain a better understanding of the cognitive processing underlying the PASAT. However, having decided to adopt a hemispheric lateralisation approach takes us beyond Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory, because it is not designed to deal with laterality effects. Predictions were therefore based on theories that have been used to account for performance differences related to lateralised stimulus presentation. This strategy allowed for both the generation of more rational predictions and the comparison of two competing theories of hemispheric differences in performance.

One of these, Friedman and Polson's (1981; Friedman et al., 1982) independent resource theory, was discussed earlier. This theory was selected because it maintains that hemispheric differences in performance are the result of varying degrees of divided attention. As such, any support for this theory found in Experiment 2 can also be taken as supporting the divided attention theory outlined earlier. The assumption here is that any improvement in performance associated with a reduction of the division of attention will indicate that divisions of attention are, at least partly, responsible for errors.

The second theory, the selective activation theory of Kinsbourne (1975), was chosen because Friedman and Polson (1981) see this theory as being diametrically opposed to their own. The selective activation theory is a well established theory of attention which has been extensively used to account for findings in the hemispheric differences research. The most important aspect of the selective activation theory for present purposes is that it sees attention as being distributed across space rather than between or within the cerebral hemispheres, According to Kinsbourne (1975), the direction of attention to either the left or right side of space is dependent on which hemisphere is most engaged, or activated, at the time. For example, if the left cerebral hemisphere is engaged in a task, and the right hemisphere is not, then the left hemisphere should be "primed" for attention relative to the right. The overall gradient of attention would be biased toward the right hemispace (the area of space to the right of the subject's nose). If a stimulus was then presented to the right visual field (RVF), that is, to the activated left hemisphere, then processing should be more rapid and efficient than if the stimulus had been presented to the left visual field (LVF), that is, to the un-primed right hemisphere.

Given the assumption that the left hemisphere is almost constantly engaged by the need to generate and articulate the verbal response during the PASAT, the selective activation theory maintains that attention should almost always be directed toward the right hemispace. In relation to the first measurement approach used in Experiment 2, which was a comparison of responses as a function of the hemisphere to which the first stimulus in the relevant pair was directed to, the theory would predict that the accuracy of response *n* should be facilitated by the presentation of stimulus *n* to the RVF, that

is, to the activated left hemisphere. Stimuli directed to the right hemisphere, which is not engaged, will cause a switching of attention and therefore disrupt processing, resulting in lower accuracy.

Turning now to the second measurement approach used in Experiment 2, a comparison of responses as a function of which hemisphere each of the relevant stimuli were directed to, the selective activation theory would predict that the highest level of accuracy would result when both of the stimuli were presented in the RVF. In contrast, it would also predict that performance would be worst when attention was required to switch most often, which, assuming that the response task is at least partly lateralised in the left hemisphere, would be when both stimuli were presented to the LVF, that is, the right hemisphere. This sample of all the possible stimulus combinations is adequate to test the theory.

If it is assumed that the attentional load on the left hemisphere is fairly constant in response terms, as this is where operations involved in the motor task of speech articulation should take place, then Friedman and Polson's (1981) independent resource theory makes quite different predictions from the selective activation theory. The former theory maintains that the division of attention inherent in dual-task performance will be lower when the necessary information processing operations can be shared between the cerebral hemispheres. The division of attention will be higher, relatively, and performance worse, when a single hemisphere must be involved in both the tasks.

Therefore, if stimulus *n* is presented in the RVF it is assumed that it will largely be

processed in the left hemisphere, which is subject to constant attentional demands in the form of the response sub-task. A division of attention is therefore created within the left hemisphere. A stimulus presented in the LVF, however, does not place additional demands on the processing capacity of the left hemisphere. The division of attention, therefore, is between the hemispheres, a situation which Friedman and Polson (1981) maintain is less detrimental to performance. Therefore, the division of attention should always be lowest, and performance for response *n* most accurate, when stimulus *n* is directed to the right, or unoccupied, hemisphere. When considering the lateralisation of both the stimuli associated with a particular response, performance should be best when neither stimulus adds to the attentional load of the left hemisphere, that is, when both are directed to the right hemisphere, and worst when both are directed to the left hemisphere.

On the basis of past and present findings, predictions could also be made for the effects of the mode and rate of stimulus presentation and subject sex. The changes necessary to adapt the task to lateralised presentation required that the SD for the visual stimuli be considerably shortened. Sampson (1956) found that shorter SDs generally had a detrimental effect on performance, but that this effect also depended on the combined duration of SD and ISI. As this total duration was unchanged for the visual task relative to Experiment 1, it was predicted that any detrimental effect caused by the shortened SD would be small. Any such change was expected to reduce the superiority of performance found for the visual task at equivalent SD and ISI durations.

Lateralised stimulus presentation, however, did raise some interesting issues in

relation to the degree to which the auditory and visual sensory pathways are known to be structurally lateralised in the human brain. Although auditory stimuli have been used with success in the study of the lateralised cognitive processes (Hellige, 1990), in neurological terms there is an element of uncertainty as to how complete or effective the lateralisation of an auditory stimulus can be when it is known that each ear has both contralateral and ipsilateral projections. Provided the stimulus is presented with the appropriate degree of retinal eccentricity in each hemifield, it is known that visual input will be only to the contralateral hemisphere. Therefore, in as much as the paced serial addition task was influenced by divided field presentation, the effects should be greater for the visual mode (Hellige, 1990).

The lateralisation of stimulus presentation was not expected to have any direct effect on the response to pacing. The pattern of CI scores across mode and sex was expected to show the characteristic decrement as a function of faster speed of presentation. As the elements of the paced serial addition task thought to be responsible for sex differences were unchanged, it was predicted that the performance of male subjects would be superior to that of female subjects. However, McGlone (1980) points out that the female brain may be less lateralised than the male brain. Any effects of divided field presentation may, therefore, be more pronounced for male subjects.

In summary, Experiment 2 tested the opposing predictions made for Friedman and Polson's (1981) independent resource theory and Kinsbourne's (1975) selective activation theory in respect of lateralised stimulus presentation for paced serial addition. The hypothesis being tested was that paced serial addition performance is at least partly

determined by divided attention deficits in controlled information processing. Findings consistent with the predictions based on the independent resource theory would provide support for the divided attention theory, and help to clarify the nature of the cognitive processes involved in paced serial addition performance.

Method

Subjects

The subjects were 8 males and 8 females with a mean age of 26.6 years (males = 29.5, females = 23.8). The mean handedness quotient for all subjects was 95.13% (males = 92.75%, females = 97.50%). Subject selection, apparatus, and procedure were as described in the General Method. Methodological issues unique to Experiment 2 are discussed below.

Stimulus Presentation

For the auditory task, the subject heard each stimulus number in either the left or right ear, via a pair of stereo headphones, according to randomly generated sequences (Appendix 11). The left and right stimulus presentation was mixed rather than blocked onto one or other ear or visual field following the recommendations of Norman (personal communication). On the basis of his own (unpublished) research, he advised that the predictability of stimulus location caused by blocked presentation might

overcome any possible effects of lateralised stimulus presentation.

The same sequences of left and right stimulus presentation were used for the visual task. Lateralised presentation of the visual stimuli required the use of an additional piece of apparatus, a Hewlett Packard 6944 Multiprogrammer. The Multiprogrammer performed the stimulus timing operations necessary for divided field presentation.

For the visual task, the stimulus numbers were displayed to the left or right of the centre of the monitor. In accordance with the recommendations of McKeever (1986), the stimuli subtended a total angle of 3.0°. With the subject seated at 1.0 m from the screen, the inside edge of each stimulus was 1.5°, or 26.2 mm, from centre. At 12.0 mm in width, the outside edge of each stimulus was 2.2 °, or 38.2 mm, from centre.

Consistent with the general method of visual stimulus presentation for cerebral lateralisation, the visual stimulus duration was set at 100 ms (Hannay, 1986), and the fixation point was an illuminated dot at the centre of the screen (McKeever, 1986). The fixation point remained visible throughout the duration of the task except during stimulus and mask exposure. The mask, which followed immediately after the stimulus, illuminated a rectangular area of the screen slightly larger than the stimulus display area (left and right), and was on for a duration of 200 ms. The reason for the mask was to overcome the possibility of extended stimulus viewing time caused by the gradual luminescent decay characteristics of the screen. The combined stimulus and mask duration, at 300 ms, was equivalent to the average auditory stimulus duration, thus

ensuring that the overall task duration was constant across stimulus modality.

Practice

For Experiment 2, two extra practice trials were introduced, both at the 1.2 s presentation rate, one in each stimulus presentation modality. The reason for this addition was that subjects whose first trial in Experiment 1 was at one of the faster presentation rates, having only had practice at the slowest rate, were sometimes unprepared for the difference in speed between the practice trials and their first experimental trial. The 1.2 s practice trials in Experiment 2 served better to prepare the subjects for the faster experimental trials and reduce the stress associated with performing the tasks.

Measures

A matter of some concern for Experiment 2 was that, in comparison with the type of task normally used in cerebral lateralisation studies, the PASAT is a very coarse instrument with which to measure what may be very small differences in performance. Many of these studies use both response accuracy and reaction time as dependent measures, whereas paced serial addition studies use only the former, which is arguably the less sensitive of the two (McKeever, 1986).

In addition, in Experiment 1 it was found that some of the performance indices used occurred at very low frequencies and may have been unstable. It was also noted that the

pattern of OM errors was virtually the inverse of that found for CI scores. Given these factors, it was decided to limit the measures in Experiment 2 to only CI scores.

Analysis

As the frequencies with which stimulus *n* was presented in the left or right hemifield was not exactly equal for all the number series used, the observed score for each stimulus direction variable was divided by the total number of response opportunities within the trial for that particular variable. This resulted in a proportion which was multiplied by 100 to be expressed as a percentage. All scores reported in the results, therefore, are given in these percentage terms.

Results

Table 5 shows the mean percentages of CI scores for all subjects as functions of the stimulus modality, presentation rate, and hemifield of presentation of the first stimulus in each digit pair. The overall trend appears to be toward slightly superior performance in the visual stimulus modality, and toward greater accuracy at slower rates of presentation. For the field of stimulus presentation, there appears to be a tendency in both the auditory and visual stimulus modalities for responses related to stimulus *n* to be more accurate when stimulus *n* is directed to the left ear or visual field (right hemisphere) at the 1.2 and 1.6 s presentation rates, and to the right ear or visual field (left hemisphere) at the 2.0 and 2.4 s presentation rates.

Table 5. *Mean percentages (M) and standard deviations (s.d.) for responses scored as correct and falling within the response interval (CI) for all subjects as a function of the mode and rate of stimulus presentation and the ear or visual field in which stimulus n was presented.*

		Presentation Rate							
		1.2		1.6		2.0		2.4	
Mode	Field	M	s.d.	M	s.d.	M	s.d.	M	s.d.
Auditory	Left	52.01	22.60	72.21	24.65	73.33	22.35	84.10	16.32
	Right	51.66	24.08	65.70	19.74	74.74	22.57	86.72	15.76
Visual	Left	54.80	18.60	73.83	23.60	78.63	13.29	86.33	10.57
	Right	50.82	23.12	67.30	19.42	83.52	13.94	88.95	10.84

Figure 13 shows the trends for presentation rate and ear of first stimulus presentation more clearly. (Separate figures are provided for the auditory and visual data because the similarity in the magnitude of the scores for these two modalities makes viewing difficult within a single figure.) It can be seen that differences in accuracy as a function of the ear to which the first stimulus in each digit pair was presented are small and appear to be unstable. While there appears to be a trend for responses to be more accurate when the stimulus *n* was directed to the right ear at slower pacing rates, which would be consistent with the selective activation theory, this trend appears to be reversed at the faster rates. This reversal, however, might simply be due to instability.

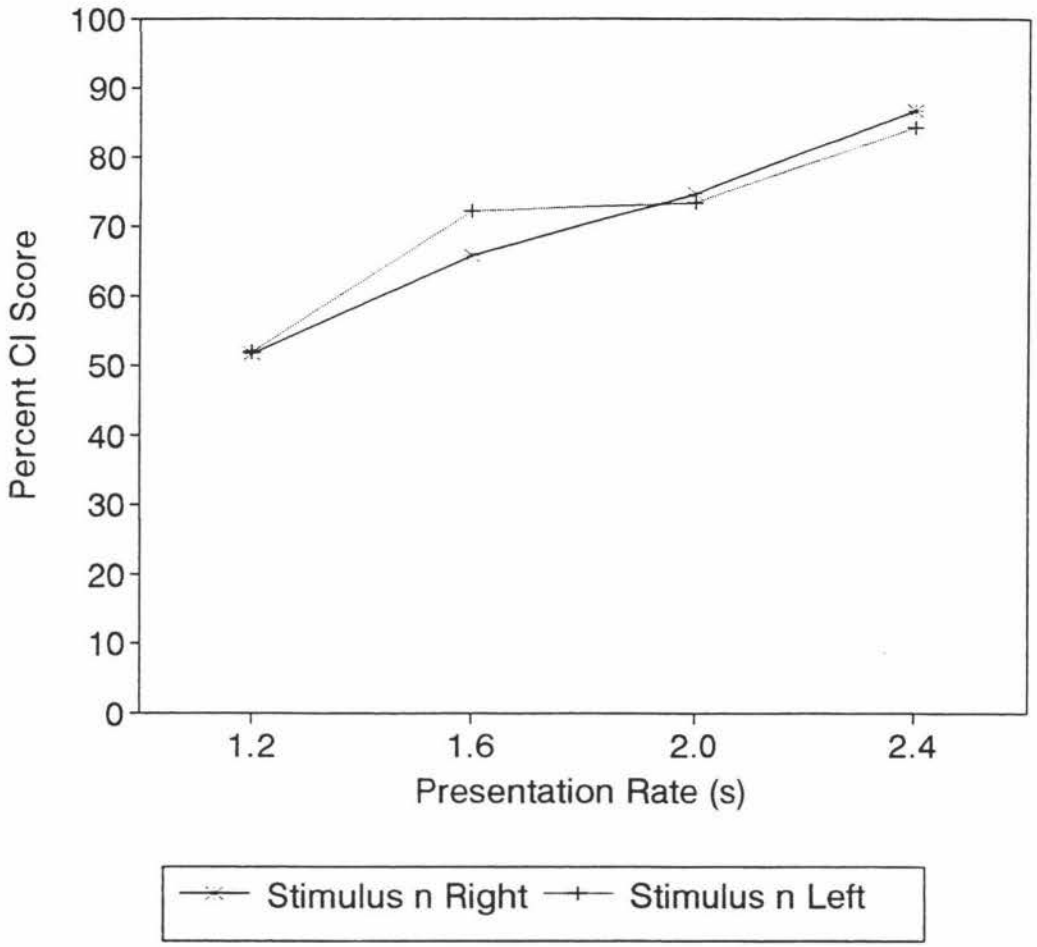

Figure 13. *Mean percentage of responses scored as correct and falling within the response interval (CI) in the auditory stimulus modality for all subjects as a function of the rate and ear of stimulus presentation.*

As Figure 14 illustrates, the trends for accuracy as a function of the visual field to which stimulus *n* was directed are similar to those seen for the auditory modality, but are a little more pronounced. Here the reversal is clearer, and the differences in response accuracy more distinct. This more obvious, albeit small, trend may reflect the greater degree of lateralisation in the visual than in the auditory sensory system as suggested earlier.

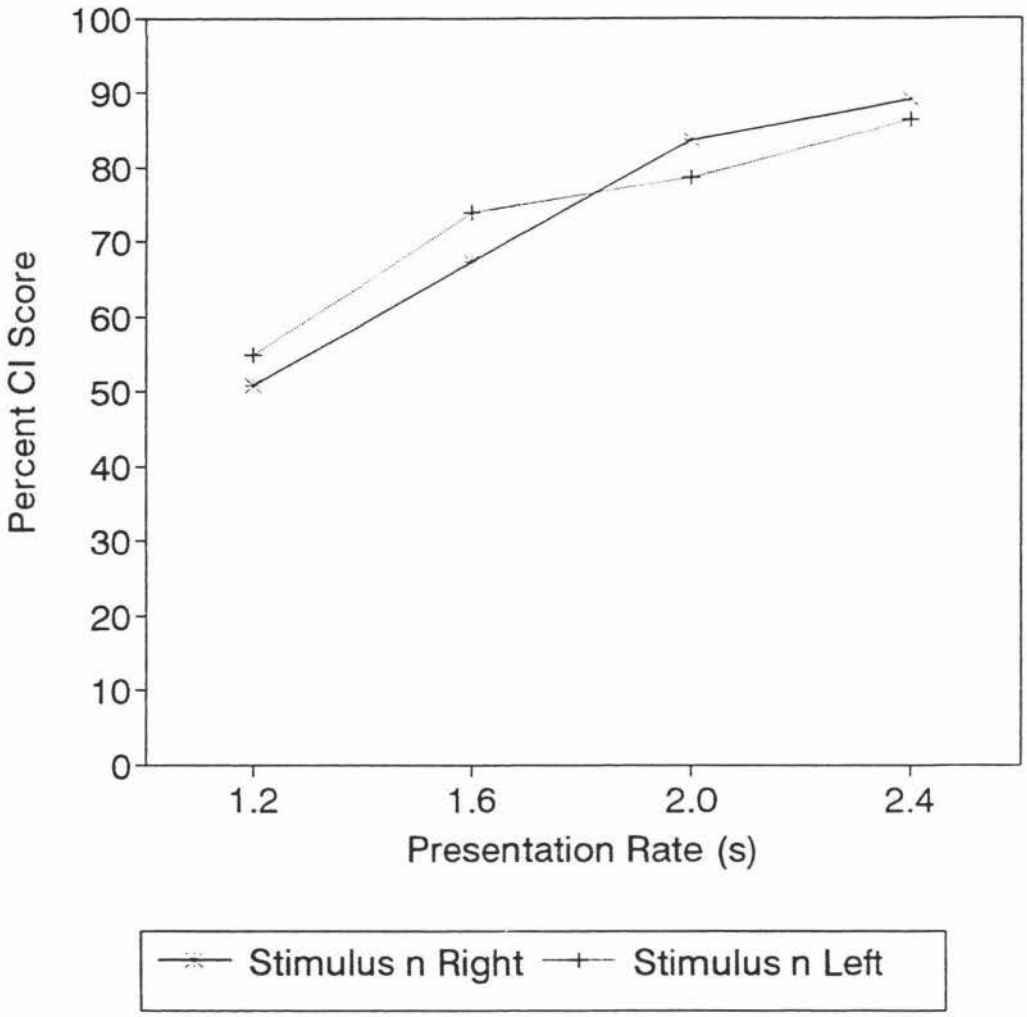

Figure 14. *Mean percentage of responses scored as correct and falling within the response interval (CI) in the visual stimulus modality for all subjects as a function of the rate and visual field of stimulus presentation.*

The standard deviations given in Table 5 suggest that variability is lower in the visual mode, particularly at the slower presentation rates. This greater consistency in responding in the visual mode may have made the apparent trends more pronounced. In effect, the pattern of responses is consistent with the independent resources theory

at the 1.2 and 1.6 s rates, but contradicts the theory at the 2.0 and 2.4 s rates, instead becoming more consistent with the selective activation theory.

The data in Table 5 were submitted to a mixed 2 x 2 x 4 x 2 (Sex x Mode x Rate x Field) MANOVA (Appendix 12H). Sex was the between-group factor and Mode, Rate, and Field were the within-subject factors. As expected, the analysis revealed a significant main effect for Rate. $F\,(3,42) = 67.54, p < .001, \eta^2 = .83$, confirming that accuracy decreased as a function of faster speeds of stimulus presentation. No other significant main or interaction effects were present. However, it can be noted that the main effect for Sex approached significance ($F\,(1,14) = 3.95, p < .07, \eta^2 = .22$), as did the Rate x Field interaction ($F\,(3,42) = 2.27, p < .10, \eta^2 = .14$). The main effect for Sex is especially interesting in that, although not quite reaching significance, it accounted for 22% of the variance and was in the opposite direction to the sex effect found in Experiment 1. That is, in general females outperformed males in Experiment 2.

Table 6 presents the data for the second measurement approach used in Experiment 2. Here, responses are given as a function of whether both the stimuli on which each response was based were presented in either the left (LL) or right (RR) ear or visual field. In the auditory modality the percentage of CI responses appears to be very similar for both the LL and RR conditions. In the visual modality a slight trend is detectable, and this appears to be similar to that found for the visual modality on the first measurement approach used in Experiment 2.

Table 6. *Mean percentages (M) and standard deviations (s.d.) for responses scored as correct and falling within the response interval (CI) for all subjects as a function of the mode and rate of stimulus presentation and the ear or visual field to which both stimuli related to each response were presented (LL = left-left, RR = right-right).*

		Presentation Rate							
		1.2		1.6		2.0		2.4	
Mode	Field	M	s.d.	M	s.d.	M	s.d.	M	s.d.
	LL	51.77	28.00	71.43	28.80	74.78	19.39	85.71	19.98
Auditory	RR	53.65	27.47	69.79	22.07	76.82	22.62	89.84	17.01
	Mean	52.71	27.74	70.61	25.44	75.80	21.01	87.78	18.50
	LL	52.68	20.00	73.33	26.90	81.36	16.00	84.15	14.75
Visual	RR	48.18	27.00	63.28	19.50	85.68	20.58	85.94	12.81
	Mean	50.43	23.50	68.31	23.20	83.52	18.29	85.05	13.78

Despite the fact that response accuracy for the RR condition was higher than in the LL condition in the auditory modality at the 1.2, 2.0, and 2.4 s presentation rates, the overall similarity between the conditions can be clearly seen in Figure 15. No real trend toward superiority for one or other condition or the reversal of a trend can be discerned. In the visual modality, however, a trend similar to those found earlier does appear to be present.

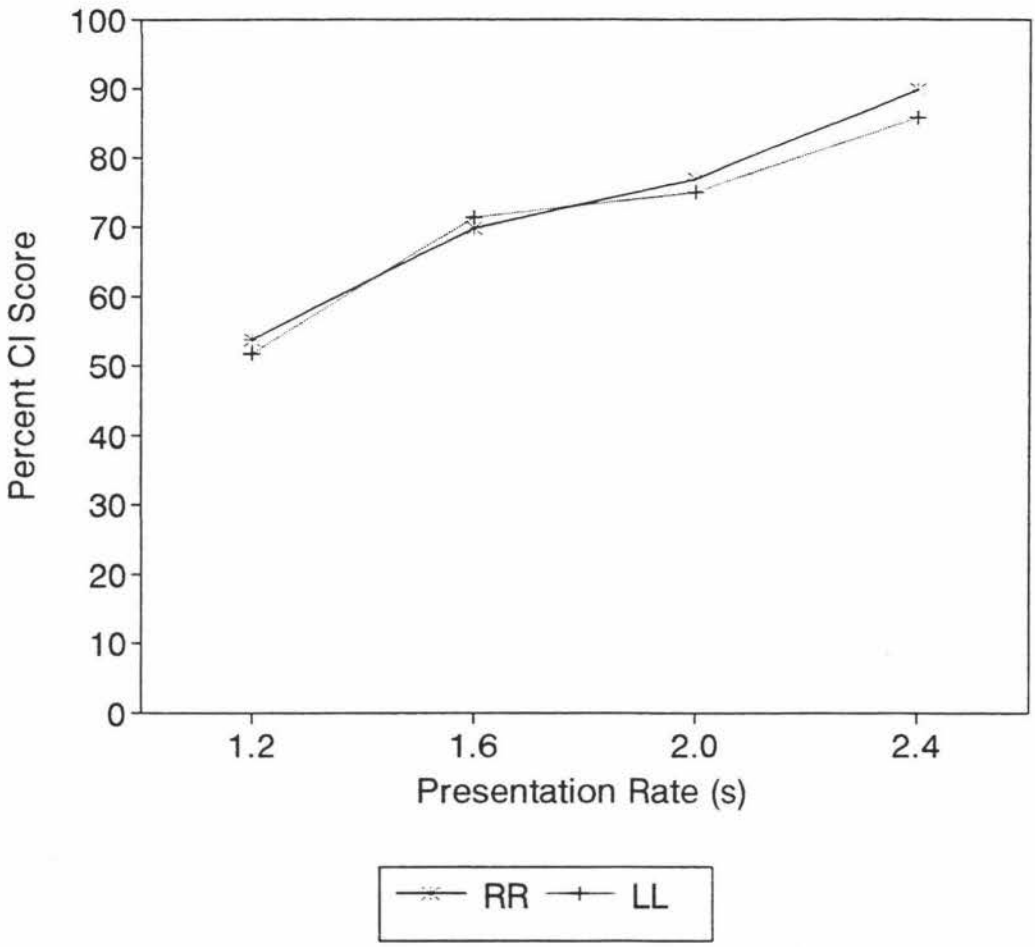

Figure 15. *Mean percentage of responses scored as correct and falling within the response interval (CI) in the auditory stimulus modality for all subjects as a function of presentation rate and the ear to which both stimuli related to each response were presented (LL = left-left, RR = right-right).*

Inspection of Figure 16 reveals that, again, a pattern is present in the results. As in Figures 13 and 14, an apparent superiority of responding for stimuli presented in the left visual field is present at the 1.2 and 1.6 s presentation rates - consistent with the independent resources theory. At presentation rates slower then 1.6 s, however, the pattern changes and is more consistent with the predictions of the selective activation

theory. For this second measure such a trend seems to be present only in the visual modality.

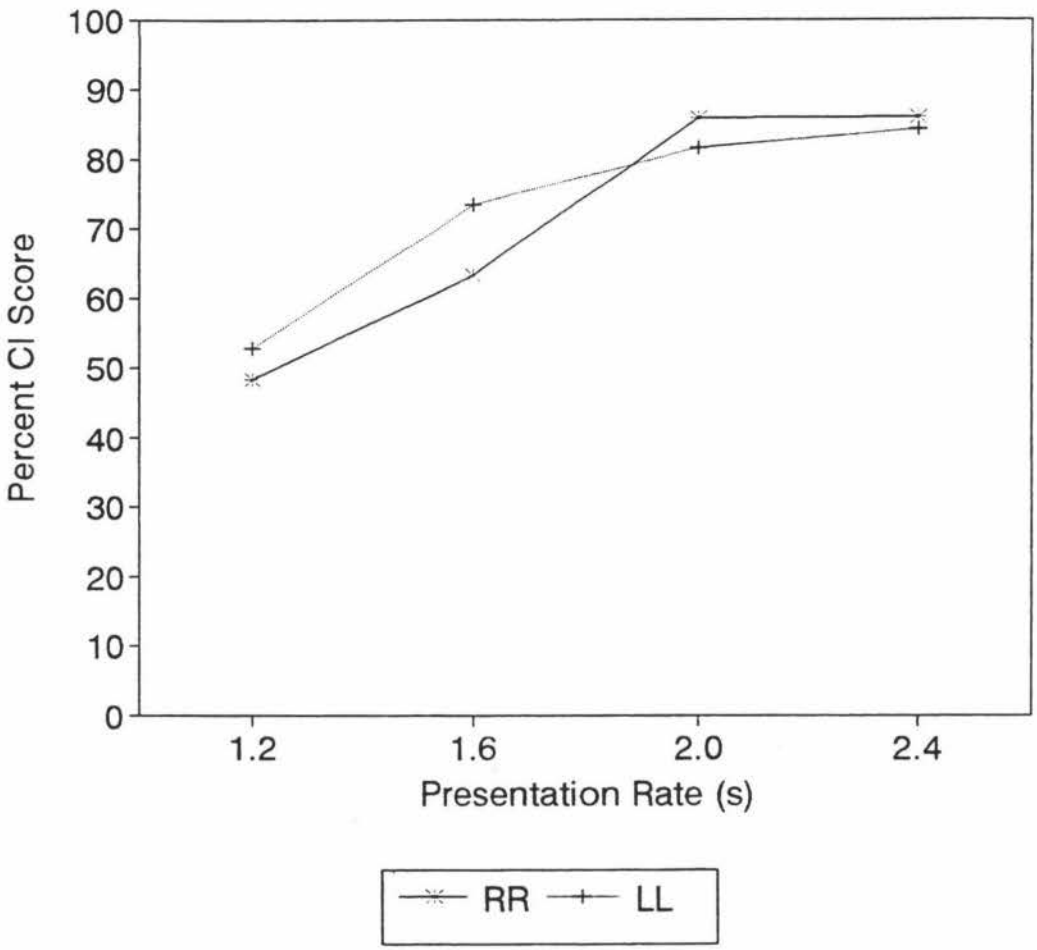

Figure 16. *Mean percentage of responses scored as correct and falling within the response interval (CI) in the visual stimulus modality for all subjects as a function of presentation rate and the visual field in which both stimuli related to each response were presented (LL = left-left, RR = right-right).*

A mixed 2 x 2 x 4 x 2 (Sex x Mode x Rate x Order) MANOVA (Appendix 12I) on the data in Table 6, in which Sex was the between-group factor and Mode, Rate, and Order were the within-subject factors, gave very similar results to the analysis of the

data in Table 5. Again, a significant main effect for Rate, F (3,42) = 45.67, $p < .001$, $\eta^2 = .77$, was present; however, this was moderated by a significant Mode x Rate interaction effect, F (3,42) = 2.79, $p < .05$, $\eta^2 = .17$. As indicated by the data in Table 6, the effect for Rate, when collapsed across Order, is toward greater accuracy as a function of slower pacing. In general, accuracy in the auditory mode appears to be slightly higher than in the visual mode. This is not the case at the 2.0 s rate, however, which probably accounts for the Mode x Rate interaction. No other significant main or interaction effects were present, however, it can again be noted that the main effect for Sex approached significance (F (1,14) = 3.57, $p < .08$, $\eta^2 = .20$), as did the Sex x Mode interaction (F (1,14) = 3.69, $p < .08$, $\eta^2 = .21$). This interaction effect, which accounted for 21% of the variance, reflects the fact that males tended to perform better in the visual than in the auditory modality, whereas the opposite tended to be true of female subjects.

Discussion

The general hypothesis for Experiment 2 was that errors on paced serial addition are the result of divided attention deficits in controlled processing. In order to test this hypothesis, predictions were generated for two theories designed to account for performance differences found in the dual-task and lateralisation literature. Although the results indicate trends consistent with both theories, they failed to reach significance. Thus, no support was found for either the independent resources theory of Friedman and Polson (1981) or the selective activation theory of Kinsbourne (1975). Nor, therefore, was support found for Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977)

general theory of automatic and controlled information.

In the context of the present study, support for the divided attention theory would have provided an important confirmation of earlier speculations and a contribution to an improved understanding of the cognitive processes underlying paced serial addition performance. In the context of wider PASAT research and use, such a finding would have represented an advance in our understanding of the cognitive processes involved in paced serial addition. Furthermore, Experiment 2 could potentially have contributed support to one or other of two important competing theories in the area of attention research. Despite this failure to find support for the hypothesis, the results of Experiment 2 do suggest some interesting trends in response accuracy, and some valuable lessons about paced serial addition research might be learned.

Returning to Figures 13 (p. 105) and 14 (p. 106) , it can be seen that, at the 1.2 and 1.6 s presentation rates, the accuracy of performance for stimuli presented in the LVF or ear (right hemisphere) is higher than for stimuli presented in the RVF or ear (left hemisphere), as was predicted by the independent resources theory. At the 2.0 and 2.4 s presentation rates, however, the trend appears to be reversed, and is more consistent with the predictions derived from the selective activation theory. A similar trend can be seen in Figure 16 (p. 110) for the LL and RR conditions in the visual modality. That this trend can be observed in three of the four measurement approach x modality conditions in Experiment 2, and that it is more pronounced in the visual modality, which may be capable of giving a clearer indication where small effects are concerned, might suggest that these small trends reflect real differences. Given the high overall

attentional demands of the PASAT, it is likely that any performance differences brought about by stimulus lateralisation will be very small. In fact, the largest effect associated with stimulus presentation in Experiment 2 was the Rate x Field interaction, which, at $\eta^2 = .14$, only accounted for 14% of the observed variability. This, coupled with the fact that percent correct decisions might not be a very sensitive measure of laterality differences suggests that Experiment 2 may have lacked sufficient statistical power to detect any lateralisation effects. This issue will be taken up again in a later section.

Insofar as the observed trends are real, they suggest a facilitation of response accuracy when stimuli are directed to the hemisphere engaged in the verbal response at slower rates of stimulus presentation, which becomes an inhibitory effect at faster presentation rates. The observed differences are small, and by comparison the variance is large (see Table 5, p. 104), but the pattern of responses and the near significant Rate x Field interaction effect, F (3,42) = 2.27, p = .095, η^2 = 0.14, suggest some important theoretical and methodological implications for future research.

First, theories proposing a single underlying mechanism for all paced serial addition performance could prove to be inadequate. Evidence presented earlier suggested that paced serial addition performance related to other variables in a fairly complex manner. An example was the higher correlation with a test of memory (RAVLT) for a PASAT trial at a slow presentation rate than for a trial at a faster presentation rate. The present results also give some indication that the nature of the information processing underlying paced serial addition performance may be, to some degree, dependent on the presentation rate. It may be that at faster presentation rates questions of overlapping or

simultaneous processing are of primary importance, while at slower rates elements such as memory become more central to performance. This represents a departure from conventional views, which tend to see the information processing involved in paced serial addition performance as being of a constant nature, but functioning at different levels of efficiency depending on the rate of stimulus presentation.

In methodological terms, it appears that the concerns expressed earlier as to the adequacy of sensitivity of the paced serial addition task for an investigation of potentially very small inter-hemispheric differences may have been confirmed by the results. Although some interesting trends are visible, they failed to reach significance. There are, however, a number of ways in which the efficacy of the methodology might be enhanced without the need for fundamental design changes. These possible changes are discussed in a later section on future research.

In relation to the other predictions made, the effect of presentation rate clearly conformed to the established pattern. Across all variables the accuracy of performance declined as a function of faster pacing. The (non-significant) superiority of performance in the visual mode appears to confirm the prediction that the shorter SD would have a detrimental effect on accuracy in the visual modality. This finding is consistent with the observations made by Sampson (1956). In the absence of evidence to indicate otherwise, it is also consistent with Sampson and MacNeilage's (1960) rescanning theory, which states that shorter stimulus viewing times limit the efficiency of processing. In Experiment 2, the subject had a shorter time to inspect the stimulus, but a longer time to respond. According to the divided attention theory this may have been expected to

result in greater accuracy.

However, alternative explanations are also possible. It may be that the 200 ms mask that followed each visual stimulus acted as a form of distraction, and possibly contributed further to any division of attention present in the task. It is also possible that lateralisation of the stimuli somehow caused a reduction of CI scores in the visual modality. These possibilities would be interesting areas for further investigation.

Although the effect for sex of subject did not quite reach significance, the interesting fact was that in Experiment 2, females generally outperformed males, the reverse of the effect found in Experiment 1. The failure to find a clear-cut effect for sex of subject may have occurred for a number of reasons. For one, it may be that sex differences in paced serial addition performance do not exist. This, however, would be inconsistent with the results of Experiment 1 and with the findings of the largest standardisation study of PASAT scores ever conducted (Brittain et al., 1991). It might also be possible that the small sample size used left the results open to the influence of individual differences. It is not inconceivable that the presence of one exceptionally high performing subject in the female group, and one very poor performer in the male group, would be sufficient to negate the sex difference, particularly in groups of only eight subjects. This possibility is further investigated in a comparison of the results from Experiments 1 and 2, in the General discussion section.

GENERAL DISCUSSION

To briefly recapitulate the results of Experiment 1, the experiment aimed to replicate, clarify, and extend the findings of Caroselli et al. (personal communication, 1994), in order to better understand the nature of the cognitive processes underlying PASAT performance. Their findings had indicated that, when administered under equivalent experimental conditions, the accuracy of performance for a visual paced serial addition task was superior to performance for an auditory task. In Experiment 1 it was hypothesised that this superiority was due to a stimulus modality-specific factor in an otherwise similar underlying form of information processing. The patterns of results for a number of performance indices, as a function of stimulus presentation rate and task duration, were compared to show that the nature of the information processing underlying paced serial addition performance was independent of the stimulus modality effect. The results were consistent with the hypothesis, and were interpreted in terms of a theory of divided attention.

Continuing from Experiment 1, Experiment 2 also aimed to elucidate the nature of the cognitive processes underlying PASAT performance by conducting a test of the divided attention theory. It was hypothesised that the creation of a controlled functional division of attention within the paced serial addition task would result in measurable performance differences. These differences would provide evidence that divided attention deficits in controlled processing were at least partly responsible for errors on the PASAT. The test involved defining paced serial addition in dual-task terms and adapting the task for lateralised presentation, in an effort to distribute the attentional load inherent in the task between the cerebral hemispheres and show that a greater

functional division of attention would result in lowered accuracy. Predictions were generated from two competing general theories of hemispheric differences in performance.

The results were not consistent with the predictions. Although some small trends appeared to be present, these were not as expected and did not reach statistical significance. This failure to support the divided attention theory, which maintains that the overlap of processing elements caused by faster stimulus presentation rates results in an attentional overload, indicates that other factors may be important determinants of paced serial addition performance.

In general, the results for the experiments conducted in the present study are consistent with the findings from previous PASAT research. The stimulus modality effect suggested by Sampson and MacNeilage (1960) and Caroselli et al. (personal communication, 1994) was confirmed and clarified. This work was also extended by the use of performance indices suggested by Sampson (1956, 1961; Sampson & MacNeilage, 1960). The findings for these indices were consistent with earlier indications, and also suggested that the cognitive processes underlying paced serial addition performance operated in a similar fashion across stimulus presentation modality. An unexpected result, the superiority of paced serial addition performance for males, was found to be consistent with the findings from some previous research, for example, the study by Brittain et al. (1991).

The greatest inconsistency thus far left unexplained was the marked gender difference found between the two experiments. While male subjects clearly outperformed female

subjects in Experiment 1, Experiment 2 produced a reversal of this pattern, with females outperforming males. Although the effect for Sex did not quite reach significance in Experiment 2, it did account for 22% of the observed variance, which is of similar magnitude to the 26% of variance accounted for by the Sex effect in Experiment 1. Table 7 presents for comparison the mean frequencies and standard deviations of CI scores as a function of stimulus modality and presentation rate for male and female subjects in Experiments 1 and 2.

Table 7. *Mean frequencies (M) and standard deviations (s.d.) for correct responses falling within the response interval (CI) for male and female subjects in Experiments 1 and 2 as a function of the mode and rate of stimulus presentation.*

			Presentation Rate							
			1.2		1.6		2.0		2.4	
Mode	Sex	Expt.	M	s.d.	M	s.d.	M	s.d.	M	s.d.
Auditory	Male	1	14.38	3.38	20.50	3.46	21.88	3.76	25.50	1.41
	Male	2	13.00	5.66	18.00	5.73	19.63	6.89	24.00	3.78
	Female	1	12.13	4.58	15.50	3.78	18.38	4.17	22.88	3.44
	Female	2	18.25	6.92	23.50	5.21	24.63	5.18	27.00	4.34
Visual	Male	1	19.38	6.35	23.00	4.31	26.38	2.50	28.63	1.19
	Male	2	13.88	5.28	18.63	6.16	22.75	3.15	25.25	2.82
	Female	1	14.63	3.89	21.75	6.30	23.50	4.14	24.75	2.87
	Female	2	17.75	4.89	23.63	4.72	25.88	3.14	27.25	2.87

The data in Table 7 reveal a complex pattern of interaction between Mode and Sex across Experiments 1 and 2. This was confirmed by submitting the data to a mixed 2 x 4 x 2 x 2 (Mode x Rate x Sex x Experiment) MANOVA (Appendix 12J). Mode and Rate were the within-subject factors, while Sex and Experiment were the between-group factors. The analysis revealed significant main effects for Rate, $F\,(3,84) = 151.60$, $p < .001$, $\eta^2 = .84$, and Mode, $F\,(1,28) = 32.18$, $p < .001$, $\eta^2 = .54$. Significant interaction effects were also found for Experiment x Sex, $F\,(1,28) = 8.19$, $p < .01$, $\eta^2 = .27$, and Experiment x Mode, $F\,(1,28) = 12.79$, $p < .001$, $\eta^2 = .31$. No other significant main or interaction effects were present. The effect for Rate was to be expected, and does not warrant further discussion. However, the other significant effects do require clarification.

The main effect for Mode reflects the fact that on average, across Rate, Sex, and Experiment, scores in the visual modality were higher than in the auditory modality. Any comparison involving Mode must, however, be limited by the knowledge that the methodological changes made to the stimulus exposure duration for the visual task for Experiment 2, but which were not necessary for the auditory task, have introduced a systematic bias in the results between the two experiments. The outcome of this was that the effect for Mode in Experiment 2 was not significant in any of the analyses conducted. Therefore, in the comparison of the two experiments, the Experiment x Mode interaction effect found is indicative of the contrast between superior visual modality performance in Experiment 1 and the similarity of performance across the two modalities in Experiment 2.

Experimentally induced bias is not so great a problem where the auditory task is concerned. Essentially, the only difference between the first and second studies for this task was the presence of two additional practice trials. This was constant across Mode, Rate, and Sex, however, so any improvement in performance should also be constant. A comparison of CI scores shown in Table 7 for the auditory task only reveals the reason for the significant Experiment x Sex interaction effect, which accounts for 27% of the observed variance. Lateralisation of the auditory stimuli appears to have lowered the performance of males in Experiment 2 relative to that of males in Experiment 1. The difference is fairly small, averaging 1.91 CI responses across the four presentation rates. The effect of lateralisation for females, however, appears to have been quite the reverse of that found for males. The scores for females in Experiment 2 were, on average, 6.12 CI responses *higher* than those observed for females in Experiment 1. The suspicion that lateralising the paced serial addition task in Experiment 2 might be complicated by gender differences seems to have been justified (p. 99).

Notwithstanding the methodological differences between the experiments for the visual task, the overall pattern of difference was the same as that described for the auditory task. Such patterns of change would be very difficult to explain in terms of any differential effect between the sexes caused by the small increase in practice, which leaves three plausible explanations. One is that the subjects in each experiment were drawn from different subgroups of the population. This, however, is unlikely. For both experiments the subjects were recruited from the same University department in the same way.

The two remaining possibilities each require further investigation. One, mentioned in the Discussion section of the second study, is that the presence of a few exceptionally high or low performing subjects within the small samples used may be responsible for the differences as a function of Sex between the Experiments. This possibility can be assessed by computing a simple performance index for each subject and subjecting these to visual inspection. Table 8 shows the average CI scores in the auditory stimulus presentation modality, collapsed across presentation rate, for each subject according to Sex and Experiment.

Table 8. *Mean number of responses scored as numerically correct and falling within the response interval (CI) in the auditory stimulus presentation modality, collapsed across presentation rate, for each subject as a function of sex and Experiment.*

	Male Subjects		Female Subjects	
Subject	Experiment 1	Experiment 2	Experiment 1	Experiment 2
1	18.75	26.75	18.25	29.25
2	19.75	14.00	19.00	23.25
3	22.75	18.50	12.00	19.75
4	18.00	13.25	23.25	29.75
5	21.00	20.00	15.00	25.25
6	21.25	23.25	15.50	18.25
7	24.50	12.25	20.50	17.50
8	18.50	21.25	14.25	23.70
Mean	20.56	18.66	17.22	23.34

Table 8 shows that the range of mean CI scores for male subjects in Experiment 1

was from 18.00 to 24.50, with a mean of 20.56. For male subjects in Experiment 2, the range was greater, 12.25 to 26.75, with a slightly lower mean of 18.66. Only one subject in Experiment 2 scored higher than the most accurate subject in Experiment 1, but three subjects can be seen to have scored appreciably lower than the least accurate subject in Experiment 1. Thus, the mean for Experiment 2 has greater associated variability and has been reduced by the atypically low scores of three subjects. Therefore, it is possible that the lower accuracy of male subjects in Experiment 2 was at least partly due to the presence of a few subjects who performed unusually poorly.

The scores of female subjects in Experiment 1 range from 12.00 to 23.25, with a mean of 17.22, and for Experiment 2 the range is from 17.5 to 29.75, with a mean of 23.34. While the ranges are of similar magnitude, the distribution of scores between the two groups of female subjects clearly is not. Fully half of the female subjects in Experiment 1 scored lower than the least accurate female subject in Experiment 2. Furthermore, five of the eight female subjects in Experiment 2 scored the same as or higher than the most accurate female subject in Experiment 1. While the two female subjects who scored 29.25 or more in Experiment 2 might be said to be atypical, this still leaves almost half who scored higher than the best score in Experiment 1.

The differences in scores between Experiments 1 and 2 for female subjects are not easily explained in terms of a small number of extreme scores, as were the differences observed for male subjects. For the male subjects, variability of the scores for Experiment 2 was large in comparison to the mean difference between the two experiments. For the female subjects, on the other hand, the variability of scores has

remained at a very similar level, and the higher accuracy observed in Experiment 2 appears to be a general rather than isolated trend. This brings us to the third possible explanation for the performance differences between the two studies, which is that lateralisation of the stimuli might actually have a detrimental effect on the performance of males and a beneficial effect on the performance of females.

The question arises as to how these gender differences are to be explained. As previously noted, sex differences in cognitive function are held by many to be the outcome of differences between males and females in brain organisation. McGlone (1980), in her comprehensive review of the relevant findings in the area, concluded that there was substantial evidence to suggest that the female brain is organised less along the lines of lateralisation than is the average male brain. That is, the male brain tends more strongly toward the lateralisation of function. It may be possible, therefore, that the male brain, which is capable of performing a task at a certain level when the stimuli are received in both cerebral hemispheres, is relatively disadvantaged when information received by one hemisphere must be transmitted to the other in order to complete the necessary information processing. Female subjects, however, having less functional lateralisation, may be better able to perform a task when the stimuli must be transmitted between the cerebral hemispheres.

The possible mechanism for such differences would currently be a matter of speculation However, there are some findings in the literature which may have relevance. For example, Springer and Deutsch (1993) note that qualitative differences in the shape of the corpus callosum have been found to exist between males and

females. Such a difference may indicate a differential between males and females in the way they transmit information between the cerebral hemispheres.

The superior performance of females with lateralised stimuli might also be explained in terms other than those involving the transmission of information between the hemispheres. As noted earlier, Robertson (1990) found that the degree of unilateral left visual field neglect was negatively related to PASAT scores, that is, greater neglect was associated with lower PASAT scores. This finding would appear to implicate the right cerebral hemisphere as being of some importance in PASAT performance in general. In respect of the present findings, this might indicate that males, if their brains are assumed to be more strongly left-lateralised than those of females, experienced greater difficulty in performing the information processing involved in paced serial addition when the stimuli were directed to the right hemisphere. Females, on the other hand, if their brains are assumed to be more balanced in hemispheric terms, may have been able to perform the information processing just as, or even more efficiently, regardless of which hemisphere the stimuli were directed to.

This explanation is consistent with the multiple-resource limited-capacity theory of Freidman and Polson (1981). According to this theory, information processing in one hemisphere could be facilitated by the increase in resource allocation resulting from the simultaneous performance of processing in the other hemisphere. It may be that the lateralised task was more difficult for males because their brains are more left-lateralised and the processing involved in paced serial addition is more generally carried out in the left hemisphere. If this were true, then right hemisphere facilitation might not occur for

males on the lateralised paced serial addition task. Females, if they tend to perform a greater proportion of the processing involved in paced serial addition in the right hemisphere, may experience facilitation when the stimuli are lateralised.

Limitations of the Present Study and Future Research

One of the main foci of the present study was to overcome some of the methodological problems found in earlier studies. Although this was achieved, there remained the problem of PASAT sensitivity, particularly in relation to the detection of possibly subtle hemispheric differences. Future research in this area would clearly need to address this issue of sensitivity. A related issue is the statistical power of the analysis used. Consideration of power is especially important because any laterality differences on a task such as the PASAT will be small and thus difficult to detect. One way to enhance the statistical power of the design would be to use a larger sample of subjects. Another potentially useful strategy would be to reduce variability by selecting a homogenous sample.

In the present study, the sample was assumed to be reasonably homogenous in respect of a number of factors, such as age and intelligence, which are known to be important correlates of paced serial addition performance. This assumption was based on the fact that the subjects were all drawn from a population of university undergraduate students. However, the individual performance differences in the present study were large, and might potentially be reduced by experimental or statistical control of known co-variates. Although the analysis used in the present study does control for quantitative differences

between individuals, the possibility that qualitative differences might exist calls for greater experimental control and, hence, greater statistical power.

Another way to improve the sensitivity of the task might be to augment the single independent variable used. Although indices of paced serial addition other than CI scores can be used, and some of these were included in Experiment 1, they are all essentially combined functions of the numerical accuracy of the response and its temporal relationship to the following stimulus, and can not be considered to be separate independent variables. McKeever (1986) expressed a preference for the use of reaction time (RT) over response accuracy for lateralisation studies, particularly for normal subjects, on the basis that it reduces the possible contamination of laterality effects due to "interhemispheric consultation" (p. 200). Unfortunately, measuring reaction time in the present study was not possible given that the necessary apparatus for timing verbal responses was not available. Moreover, there are a host of conceptual and methodological problems associated with the use of RT in a PASAT-like task. For example, it would be necessary to reconcile the response interval approach to scoring with the use of an RT measure as it would remain necessary to place some rational limit on how long after stimulus presentation a response could occur and still be said to be associated with the stimulus.

If future research were to adopt response latency as a measure for paced serial addition, a number of such problems will need to be addressed. As McKeever (1986) points out, response timing in lateralisation studies is normally used for tasks of low difficulty on which errors are unlikely. These tasks also usually involve discrete, rather than serial, responses, and are not normally interested in any reduction of accuracy as

a function of pacing. As all of these factors are vital in the study of paced serial addition, any investigation of the task in terms of stimulus lateralisation will continue to present methodological challenges. Other issues, such as speed-accuracy trade-offs, might also arise. Until these problems can be resolved, future research would probably best concentrate on using the existing dependent measure and improving the experimental design to be more sensitive to small effects.

Numerous other avenues for further research are suggested by the present study. For example, the effect of task duration remains poorly understood, and might also be approached from a divided attention standpoint. Detailed investigation of the unexpected pattern observed for INC errors in Experiment 1 is called for, particularly given the possibility that this represents an element of automatic processing. In particular, the findings for sex of subject suggest that the PASAT might be used to contribute to the study of sex differences in brain organisation and cognitive processes.

Conclusions

Although the present study has failed to yield conclusive evidence that divided attention deficits are the cause of errors in paced serial addition performance, it has succeeded in clarifying and extending the current understanding of the stimulus modality effect for paced serial addition and it has found evidence to suggest that an equivalent form of information processing underlies performance across stimulus modality. Furthermore, the present study has developed a methodological approach involving the lateralisation of stimulus presentation. Although lateralised stimulus presentation did not distinguish between the two attentional theories examined, this may have been due to

the small effect sizes involved. If real, but small, laterality effects do exist in addition to the gender differences observed, it may be that the present study lacked the statistical power to detect them. Future research must ensure that sufficient power is available to detect small effects if they exist.

The present study also demonstrated sex differences in performance that may have theoretical significance for understanding paced serial addition performance. A comparison of the results for Experiments 1 and 2 revealed that the effect of subject sex may interact with the method of stimulus presentation, and may have important implications for the investigation of organisational and functional differences between the brains of males and females.

There are also implications for the clinical application of the PASAT. One conclusion is that the visual stimulus presentation might provide a less stressful method of assessing information processing deficits for many subjects, and that the use of alternative performance indices might enhance the clinical utility of the PASAT. Another is that the observed sex differences might limit the utility of normative information based on male subjects in relation to the performance of female patients. It can also be added that further development of the lateralised stimulus presentation methodology may have some potential to increase the information yield of the PASAT in clinical settings. The present study represents an advance, albeit a small one, toward an improved understanding of PASAT performance that may be valuable in the continued development of clinical assessment and treatment.

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APPENDICES

List of Appendices

Appendix 1. Extended abstract of the study by Caroselli et al. (1993).

Paced Serial Addition with Auditory and Visual Stimuli: A Test of the General Capacity Model

The Paced Auditory Serial Addition Task (PASAT) is often regarded as a measure of general information processing capacity (Gronwall, 1990; Hicks, 1952). Diminished processing capacity in head-injured individuals would account for the PASAT's sensitivity to diffuse brain damage caused by mild head injury (Gronwall & Sampson, 1974; Gronwall & Wrightson, 1975). Nonetheless, alternative explanations are possible. Since the numbers to be added are presented auditorily, the factors that limit PASAT performance may be modality-specific, e.g., limitations of auditory working memory or interference between the aural stimuli and the patient's oral responses.

In order to test the general information processing explanation, we compared performance on the PASAT with performance on a similar task that entails visual presentation of numeric stimuli. Specific objectives of the study were: (1) to develop a computer-based visual analog of the PASAT that might have clinical utility; (2) to accumulate normative data for the visual task; and (3) to assess the comparability of the auditory and visual tasks with respect to overall level of performance and the pattern of performance across different interstimulus intervals.

Method

Subjects. Forty-eight university undergraduates (24 females, 24 males) served as subjects. No subject had a history of neurologic or psychiatric disorder.

Materials and Apparatus. The standard form of the PASAT was administered via tape recorder. The digits to be added were presented in four blocks of 50 digits each, with the interval between successive digits ranging from 2.4 sec in Block 1 to 1.2 sec in Block 4. The visual counterpart to the PASAT, which was called the Visual Addition Task (VAT), was programmed in BASIC and presented via microcomputer. There were three versions of the VAT, which differed only in presentation rate. For VAT-1, the presentation rates across the four trials blocks were identical to the PASAT rates. Presentation rates were accelerated by 15% in VAT-2 and by 30% in VAT-3.

Procedure. Subjects were assigned randomly to three groups of 8 females and 8 males each. All subjects completed the PASAT and one of the versions of the VAT. The order of PASAT and VAT administration was counterbalanced within each group. Irrespective of test, subjects responded orally.

Results and Discussion

Since preliminary analyses revealed no significant effects for order or sex, those factors were omitted from subsequent analyses. ANOVA with group as a between-subject factor indicated, as expected, that the effects of primary interest varied significantly across groups. Therefore, separate 2 x 4 (Modality x Trial Block) ANOVAS were performed for each group.

Group 1. ANOVA yielded a significant main effect for trial blocks ($p < .0001$) and a significant Modality x Trial Block interaction ($p < .005$). Although scores from both the auditory and visual tasks decreased across trial blocks (i.e., with decreasing interstimulus intervals), auditory scores showed a sharper decline. The interaction was attributable to the Modality x Trial Block Linear Trend component (see Figure 1). Thus, when presentation rates for the two tasks were equated, the PASAT became progressively more difficult than the VAT as the interstimulus interval was decreased from 2.4 to 1.2 sec.

Group 2. The corresponding ANOVA for Group 2 yielded only a significant main effect for trial blocks ($p < .0001$). Trend analysis showed that the decline across blocks was primarily linear. The absence of other significant effects indicates a striking similarity between PASAT and VAT performance when the VAT presentation rates were accelerated by 15%. (See Figure 2.)

Group 3. A significant main effect for trial blocks ($p < .0001$) was again attributable largely to the linear trend. A significant effect for modality ($p < .005$) reflected inferior performance on the visual task across all trial blocks. (See Figure 3.) This outcome indicates that, when presentation rates for the VAT were accelerated by 30%, the VAT became significantly more difficult than the PASAT.

Figure 1
Auditory and Visual Stimuli
Presented at the Same Rate

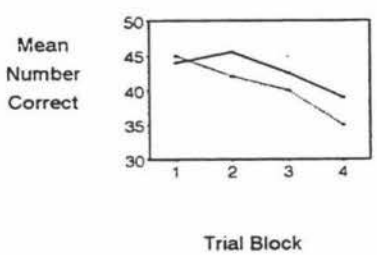


Figure 2
Visual Stimuli Presented 15%
Faster than Auditory Stimuli

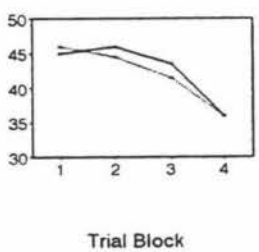
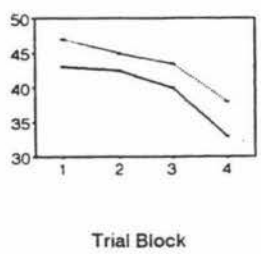


Figure 3
Visual Stimuli Presented 30%
Faster than Auditory Stimuli



Key: Dotted line = Auditory Stimuli; Solid Line = Visual Stimuli

Conclusions

1. A computer-based visual addition task (VAT) yielded a pattern of correct responses across different interstimulus intervals that closely resembles the pattern obtained from the standard PASAT.
2. VAT and PASAT performance levels were most similar when the VAT presentation rates were accelerated by 15% relative to the PASAT.
3. The similar patterns obtained with visual and auditory tasks support a general capacity explanation for PASAT performance. However, since the auditory task was more difficult than the visual tasks when presentation rates were equated, there seems to be a modality-specific component to PASAT performance in addition to the general capacity component.

Appendix 2. Subject Information Questionnaire and Edinburgh Handedness Inventory.

SUBJECT INFORMATION QUESTIONNAIRE

SUBJECT NUMBER: **SESSION DATE:**

NAME: **SESSION TIME:**

SUBJECT AGE: **SUBJECT SEX:**

HEARING: **VISION:**

HEAD INJURY HISTORY:

EDINBURGH HANDEDNESS INVENTORY*

	BEHAVIOUR	LEFT	RIGHT
1	WRITING (name)		
2	DRAWING (person)		
3	THROWING (ball)		
4	SCISSORS (cutting paper)		
5	TOOTHBRUSH (brushing teeth)		
6	KNIFE (without fork)		
7	SPOON		
8	BROOM (upper hand)		
9	STRIKING MATCH (match)		
10	OPENING BOX (lid)		
	TOTALS		

LATERALITY QUOTIENT:

*Adopted from: Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9,* 97-113.

Appendix 3. Presentation Schedule.

	SUBJECT																			
	1			2			3			4			5			6			7			8		
T	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S
1	A	2.4	14	A	2.0	8	V	2.0	5	V	1.2	4	A	1.6	9	V	1.6	9	V	2.4	14	A	1.2	2
2	A	1.6	11	V	1.6	12	V	2.4	14	V	1.6	11	V	1.2	2	A	1.2	3	V	1.2	3	V	2.4	16
3	V	2.0	5	A	2.4	13	A	2.0	7	V	2.4	13	V	2.0	7	V	2.4	13	A	1.6	11	V	1.6	11
4	V	2.4	16	V	1.2	1	V	1.6	11	A	2.4	14	A	2.0	5	V	2.0	8	V	2.0	7	A	2.0	7
5	A	1.2	2	A	1.6	10	A	1.2	1	A	1.6	12	V	2.4	13	A	1.6	12	A	2.4	16	V	1.2	1
6	V	1.2	3	A	1.2	2	V	1.2	4	V	2.0	6	A	1.2	3	A	2.4	15	A	1.2	1	V	2.0	6
7	A	2.0	7	V	2.4	15	A	1.6	10	A	2.0	8	V	1.6	10	V	1.2	4	V	1.6	10	A	1.6	9
8	V	1.6	9	V	2.0	5	A	2.4	15	A	1.2	3	A	2.4	16	A	2.0	6	A	2.0	8	A	2.4	14

	SUBJECT																			
	9			10			11			12			13			14			15			16		
T	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S	M	RT	S
1	V	2.4	16	A	1.2	1	V	2.0	7	V	1.6	10	A	2.0	5	A	2.4	15	A	1.6	10	V	1.2	1
2	A	2.4	15	V	1.2	3	A	2.0	5	V	1.2	4	V	1.2	3	V	1.2	1	V	2.4	15	V	1.6	11
3	A	2.0	6	A	2.4	13	A	1.2	3	A	2.4	14	A	1.6	12	A	1.2	4	V	2.0	6	A	2.4	16
4	V	2.0	8	A	1.6	10	A	2.4	16	V	2.4	13	V	2.4	15	V	2.4	16	A	1.2	4	A	1.6	12
5	V	1.2	2	V	2.4	15	V	1.2	2	V	2.0	8	V	1.6	9	V	2.0	7	A	2.0	8	V	2.0	6
6	A	1.6	9	V	1.6	12	V	1.6	12	A	1.2	1	A	1.2	2	A	1.6	9	V	1.2	2	V	2.4	14
7	V	1.6	10	V	2.0	5	A	1.6	11	A	2.0	5	A	2.4	13	V	1.6	12	A	2.4	13	A	2.0	7
8	A	1.2	4	A	2.0	6	V	2.4	14	A	1.6	11	V	2.0	8	A	2.0	6	V	1.6	9	A	1.2	4

KEY: M = MODE (A = AUDITORY, V = VISUAL)
RT = PRESENTATION RATE (s)
S = 30-DIGIT SEQUENCE USED FOR TRIAL (16 POSSIBLE SEQUENCES)
T = TRIAL NUMBER

Appendix 4. Sample of the Subject Response Form used for Experiment 1.

NAME: _____ DATE: _____

D.O.B. _____ TIME: _____

SEX: _____ HAND SCORE: _____

	TRIAL 1				TRIAL 2				TRIAL 3				TRIAL 4			
	RATE			1.2	RATE			1.6	RATE			2.4	RATE			2.4
	MODE (A/V)			V	MODE (A/V)			V	MODE (A/V)			V	MODE (A/V)			A
	SEQUENCE			4	SEQUENCE			11	SEQUENCE			13	SEQUENCE			14
POS	ST	RESP	IN	CO	ST	RESP	IN	CO	ST	RESP	IN	CO	ST	RESP	IN	CO
1	1				2				4				6			
2	4				1				6				8			
3	9				2				5				5			
4	9				4				3				6			
5	1				9				3				2			
6	3				5				9				6			
7	1				8				9				3			
8	5				4				3				8			
9	2				6				3				1			
10	1				4				4				1			
11	6				2				9				9			
12	9				3				8				2			
13	2				2				9				6			
14	9				6				2				5			
15	8				1				4				1			
16	4				9				1				1			
17	8				8				4				4			
18	8				3				6				5			
19	3				3				2				4			
20	8				6				5				8			
21	4				9				1				2			
22	3				5				5				8			
23	3				1				8				5			
24	2				3				1				3			
25	4				6				2				4			
26	5				4				8				3			
27	5				1				1				2			
28	6				5				2				4			
29	2				3				8				9			
30	6				8				6				9			
31	6				8				5				3			
32	5				9				6				9			
TOTAL CORRECT																

continued over...

Appendix 4 cont.

	TRIAL 5				TRIAL 6				TRIAL 7				TRIAL 8			
	RATE			1.6	RATE			2.0	RATE			2.0	RATE			1.2
	MODE (A/V)			A	MODE (A/V)			V	MODE (A/V)			A	MODE (A/V)			A
	SEQUENCE			12	SEQUENCE			6	SEQUENCE			8	SEQUENCE			3
POS	ST	RESP	IN	CO	ST	RESP	IN	CO	ST	RESP	IN	CO	ST	RESP	IN	CO
1	1				8				9				2			
2	9				6				6				9			
3	4				6				8				9			
4	9				2				1				4			
5	5				5				6				3			
6	9				9				6				4			
7	8				1				9				2			
8	6				8				3				6			
9	5				3				6				6			
10	1				8				4				3			
11	3				6				1				2			
12	4				4				8				8			
13	9				8				3				8			
14	4				9				9				3			
15	4				4				8				3			
16	3				1				4				4			
17	1				3				2				8			
18	5				2				4				1			
19	2				1				3				9			
20	8				2				5				4			
21	8				2				2				8			
22	3				4				9				9			
23	2				9				4				6			
24	3				4				8				2			
25	6				5				5				1			
26	2				6				1				3			
27	6				9				3				5			
28	1				3				5				6			
29	8				5				1				5			
30	6				3				2				1			
31	1				5				2				5			
32	1				3				5				5			
TOTAL CORRECT																

SUBJECT RESPONSE RECORD EXPERIMENT 2 SEQUENCE: 4 RATE: 1.2 MODE:

							TOTAL					LEFT/RIGHT					LEFT/LEFT					RIGHT/RIGHT					RIGHT/LEFT				
POS	FD	ST	CS	SR	RC	RI	CI	CO	II	IO	OM	CI	CO	II	IO	OM	CI	CO	II	IO	OM	CI	CO	II	IO	OM	CI	CO	II	IO	OM
1	L	1	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
2	L	4	5																												
3	R	9	13																												
4	R	9	18																												
5	L	1	10																												
6	R	3	4																												
7	R	1	4																												
8	L	5	6																												
9	R	2	7																												
10	R	1	3																												
11	L	6	7																												
12	L	9	15																												
13	L	2	11																												
14	R	9	11																												
15	R	8	17																												
16	R	4	12																												
17	L	8	12																												
18	L	8	16																												
19	R	3	11																												
20	R	8	11																												
21	L	4	12																												
22	L	3	7																												
23	L	3	6																												
24	R	2	5																												
25	R	4	6																												
26	R	5	9																												
27	L	5	10																												
28	L	6	11																												
29	R	2	8																												
30	L	6	8																												
31	R	6	12																												

RC	RI	TOTAL					LEFT/RIGHT					LEFT/LEFT					RIGHT/RIGHT					RIGHT/LEFT				
		CI	CO	II	IO	OM	CI	CO	II	IO	OM	CI	CO	II	IO	OM	CI	CO	II	IO	OM	CI	CO	II	IO	OM

Appendix 6. Scoring Template.

SEQUENCE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
RATE	1.2	1.2	1.2	1.2	2.0	2.0	2.0	2.0	1.6	1.6	1.6	1.6	2.4	2.4	2.4	2.4
STIMULUS POSITION	CORRECT RESPONSE															
2	17	9	11	5	8	14	11	15	4	13	3	10	10	14	10	14
3	10	12	18	13	12	12	6	14	7	8	3	13	11	13	8	8
4	9	10	13	18	17	8	10	9	12	4	6	13	8	11	14	11
5	12	6	7	10	17	7	9	7	13	7	13	14	6	8	13	13
6	10	14	7	4	14	14	8	12	14	10	14	14	12	8	11	11
7	7	17	6	4	8	10	14	15	18	6	13	17	18	9	15	12
8	4	13	8	6	5	9	15	12	10	3	12	14	12	11	13	11
9	5	7	12	7	11	11	15	9	7	4	10	11	6	9	9	7
10	6	5	9	3	10	11	17	10	7	5	10	6	7	2	13	10
11	13	9	5	7	8	14	12	5	7	5	6	4	13	10	10	14
12	17	9	10	15	7	10	6	9	11	11	5	7	17	11	4	12
13	11	8	16	11	6	12	11	11	6	10	5	13	17	8	3	9
14	6	14	11	11	6	17	14	12	7	6	8	13	11	11	4	6
15	11	13	6	17	5	13	8	17	15	8	7	8	6	6	7	11
16	10	5	7	12	9	5	8	12	11	10	10	7	5	2	7	13
17	6	6	12	12	8	4	8	6	6	11	17	4	5	5	11	6
18	8	13	9	16	11	5	6	6	12	9	11	6	10	9	12	5
19	5	9	10	11	11	3	4	7	11	10	6	7	8	9	8	5
20	4	4	13	11	4	3	9	8	6	9	9	10	7	12	5	4
21	5	11	12	12	7	4	13	7	7	12	15	16	6	10	10	7
22	5	12	17	7	15	6	11	11	7	11	14	11	6	10	10	6
23	8	10	15	6	10	13	10	13	8	5	6	5	13	13	3	10
24	11	8	8	5	3	13	12	12	7	4	4	5	9	8	8	17
25	12	11	3	6	3	9	10	13	8	6	9	9	3	7	9	11
26	8	17	4	9	3	11	4	6	10	10	10	8	10	7	8	5
27	11	12	8	10	11	15	3	4	9	11	5	8	9	5	6	12
28	14	5	11	11	15	12	7	8	13	14	6	7	3	6	4	11
29	6	5	11	8	10	8	14	6	10	17	8	9	10	13	12	6
30	7	10	6	8	13	8	9	3	4	17	11	14	14	18	15	8
31	11	8	6	12	14	8	3	4	10	17	16	7	11	12	15	5
32	14	4	10	11	10	8	3	7	17	18	17	2	11	12	14	10

Appendix 7. Subject Information Sheet.

THE PACED SERIAL ADDITION TEST

INFORMATION SHEET

You have been asked to participate in a study of human information processing. This study involves a test called the Paced Auditory Serial Addition Test (PASAT). The PASAT is used in clinical settings to measure the speed with which a person can process information. Information processing speed is sometimes impaired as a result of head injury.

In its current form the PASAT consists of a series of numbers presented audibly. The aim of the present study is to develop and evaluate a visual version of the paced serial addition test in which the numbers are seen rather than heard.

If you choose to participate in this study you will be asked to perform both the auditory and visual forms of the paced serial addition task. The study does not involve any deception and it will not cause you any discomfort.

This study is being conducted by Mark Stewart, a psychology graduate student, who can be contacted through the Psychology Department (address and telephone number above). The research is being supervised by Dr John Podd (office, 3504135; home, 3573490), a senior lecturer in the Psychology Department.

If you take part in the study you have a right to:

* refuse to answer any particular question, and to withdraw from the study at any time.

* ask any further questions about the study that occur to you during your participation.

* provide information on the understanding that it is completely confidential to the researchers. All information is collected anonymously, and it will not be possible to identify you in any reports that are prepared from the study.

* be given access to a summary of the findings from the study when it is concluded. A summary will be displayed on the notice board adjacent to the main office on the 2nd floor of the Psychology Department.

  If you wish to receive a personal copy of the study's findings please indicate this on the consent form, and include a contact address it can be sent to.

Appendix 8. Subject Consent and Feedback Form.

THE PACED SERIAL ADDITION TEST

CONSENT FORM

I have read the Information Sheet for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I also understand that I am free to withdraw from the study at any time, and to decline to answer any particular questions in the study. I agree to provide information to the researchers on the understanding that it is completely confidential.

I wish to participate in this study under the conditions set out on the Information Sheet.

Signed: _____

Name: _____

Phone Number: _____

Date: _____

* I wish to receive a personal copy of the findings from the study when it is concluded.

  yes / no

  (circle one)

CONTACT ADDRESS FOR THE SUMMARY: _____

_____

_____

_____

Appendix 9. Instructions to subjects: Experiment 1.

As you read on the information sheet, the task you are being asked to do is called the Paced Serial Addition Task. Your participation today will involve doing eight brief serial addition trials, each using a different series of 32 single digit numbers. On four of these trials you will hear the numbers over a set of headphones, and on the other four you will see the numbers on a computer screen. These auditory and visual trials are randomly presented, but I will tell you which type to expect just before each trial starts. You will be able to have a short break between trials, and the whole session should take about 15 to 20 minutes.

The task on each trial is the same, and it is to add pairs of numbers together in your head and say the answer out loud. As the numbers in each series range from one to nine, the maximum answer you will have to give will be 18. You do not have to give a response for the first number you hear or see in each series, but you need to remember it so that you can add it to the second number when it is presented and say the answer out loud. When the third number is presented, you should add that to the second number, that is, the one that came immediately before, and again say the answer, and so on for the rest of the numbers in the series. For example, if you heard the number three followed by the number six, what would your answer be? If the next number in the series was an eight, what would your answer be then? (If the subject remained unclear of how to perform the task, the experimenter wrote a short series of numbers down on paper and explained the procedure again until the subject could comprehend it.)

Now that you understand what to do, we will run through two very short practice trials, one auditory and one visual, so that you can get used to the equipment you will be using. This is the chair you will sit in for all of the trials; go ahead and sit down. The head rest is there to make sure you are the correct distance away from this screen, which is where you will see the numbers for the visual trials. Let's practice that now. Sit with your head in contact with the head rest and watch the screen closely. The

numbers will appear at the centre of the screen and will only be displayed briefly. Start responding as soon as you have seen the first two numbers. Try to say your answers clearly, as I will be recording them with this microphone. (The experimenter then ran the visual practice trial.) These are the headphones you will use for the auditory trials. I will tell you when you should put them on and you can take them off at the end of each trial. Put them on now and have a practice. (The experimenter then ran the auditory practice trial.)

On both of the trials you have just done the numbers were presented at a rate of one number every 2.4 s. Some of the experimental trials will be at the same speed, but most of them will be faster, which makes the task more difficult. You are certain to make some mistakes, but I would like you to do your best to give a correct answer for each pair of numbers. It is also very important that you do this as quickly as you can, as you only have a short time to give your response before the next number is presented. If you get muddled and lose track of the numbers, don't give up. Just stop responding until the next pair of numbers is presented and then start answering again. Some people find that on the faster trials it is easier to only respond to every second number, but I would like you to avoid doing this. That way you can only get half right at most, and it is possible to do better. Try your best to respond after every number.

Appendix 10. Instructions to subjects: Experiment 2.

As you read on the information sheet, the task you are being asked to do is called the Paced Serial Addition Task. Your participation today will involve doing eight brief serial addition trials, each consisting of a different series of 32 single digit numbers. The task is the same for all the trials. I will explain it to you now and you will be able to practice it before we start the experimental trials. As each number is presented I want you to add it, in your head, to the one that came immediately before and say the answer out loud. This means that you do not have to give a response for the first number in each series, but you need to remember it so that you can add it to the second number and say the answer out loud. When the third number is presented, you should add that to the second number, and so on for the rest of the numbers in the series. Each time you are only adding two numbers together. You don't have to add all the numbers together in a row and you don't have to add numbers to your own answers.

For example, if you heard the number three followed by the number six, what would your answer be? If the next number in the series was an eight, what would your answer be then?

On four of the trials you will hear the numbers over a set of headphones, and on the other four you will see the numbers on a computer screen. You won't have to do both at the same time. The numbers are also presented at four different rates, but the rate stays constant within each trial. The order in which you will do the trials is random, but before each trial I will let you know whether it is auditory or visual and what rate the numbers will be presented at. You will find that the task is quite demanding but you will be able to take a short break between trials and the longest trial only lasts a little over a minute. Now that you understand what to do, we will run through some short practice trials so that you can get used to doing the task.

This is the chair you will sit in for all of the trials; go ahead and sit down. The head rest is there to make sure you are the correct distance away from this screen, which is where you will see the numbers for the visual trials. When we do the experimental trials

later on I will use this microphone to record your responses; so try to say your answers loud and clear. These are the headphones you will use for the auditory trials. You will only have to wear them for the auditory trials, and you can take them off as soon as the numbers stop coming. On the auditory trials, the numbers are randomly directed to the left or right side, so you will only hear each number in one ear. It is impossible to predict which ear the next number will go to, and that is not what I want you to try to do. Just concentrate on doing the task as well as you can. If you are happy to go on we will do the first practice trial now. Put the headphones on with the side where the cord comes out closest to the wall. I will check each time to make sure they are the right way round. The numbers on this practice trial will come at the slowest rate, one number every 2.4 s. Say your answers out loud so I can check that you have the idea, and let me know if you have any trouble hearing the numbers. Don't worry if you make some mistakes. I'll go and start the tape now.

Now we will do another auditory practice trial, but this time the numbers will come at the fastest rate, one number every 1.2 s. This is harder, and you can expect to make more mistakes. You might find yourself getting completely muddled. If that happens, don't give up. Just stop for a moment and clear your mind, then start responding again as soon as you can. You might be tempted to respond only to every second number, as this is much easier to do, but I would like you to try your best to respond every time. I'll go and start the tape now.

Let's practice some visual trials now. The first one will be at the 2.4 s rate. Sit with your head in contact with the head rest and watch the screen closely. The first thing you will see is some instructions telling you that the trial is about to start. When these go off, a fixation point, a dot in the middle of the screen, will appear just before the first number. The fixation point will stay on for the whole trial, and it is really important that you keep your eyes on this point right through the trial. The numbers will appear a little to the left or right of the fixation point and will be followed by a mask, where a rectangular section of the screen will be lit up so that you don't see the number for any longer than is necessary. I don't want you to try to guess which side the next number will appear on, as this is at random and impossible to predict. You will find

that your eyes will want to move to whichever side the number appears on, but just bring them back so that you are focusing on the fixation point each time a number appears; its really vital that you do that. The numbers are only on the screen for a very brief time, but you should have no trouble seeing them. Call out your answers like before. I will start the trial now.

Now let's do the last practice trial. This time the numbers will come at the fastest rate again, one every 1.2 s. Remember to try your best, and if you get muddled just take a quick pause and get back into it as quickly as you can. I'll start the trial now.

Appendix 11. Number sequences used in both experiments and the visual field or ear (L = left, R = right) each number was presented in for Experiment 2.

RATE	1.2								1.6								2.0								2.4							
SEQUENCE	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16	
DIGIT/FLD	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
POSITION																																
1	8	R	6	R	2	R	1	L	4	R	8	R	9	R	9	L	1	R	8	R	2	R	1	L	4	R	6	R	8	R	9	L
2	9	L	3	L	9	L	4	L	4	L	6	L	2	L	6	L	3	L	5	L	1	L	9	L	6	L	8	L	2	L	5	L
3	1	L	9	L	9	R	9	R	8	L	6	L	4	R	8	R	4	L	3	L	2	R	4	R	5	L	5	L	6	R	3	R
4	8	R	1	R	4	L	9	R	9	R	2	R	6	L	1	R	8	R	1	R	4	L	9	R	3	R	6	R	8	L	8	R
5	4	R	5	R	3	L	1	L	8	R	5	R	3	L	6	L	5	R	6	R	9	L	5	L	3	R	2	R	5	L	5	L
6	6	R	9	L	4	R	3	R	6	R	9	L	5	R	6	R	9	R	4	L	5	R	9	R	9	R	6	L	6	R	6	R
7	1	L	8	L	2	R	1	R	2	L	1	L	9	R	9	R	9	L	2	L	8	R	8	R	9	L	3	L	9	R	6	R
8	3	L	5	L	6	R	5	L	3	L	8	L	6	R	3	L	1	L	1	L	4	R	6	L	3	L	8	L	4	R	5	L
9	2	L	2	R	6	L	2	R	8	L	3	R	9	L	6	R	6	L	3	R	6	L	5	R	3	L	1	R	5	L	2	R
10	4	R	3	R	3	L	1	R	2	R	8	R	8	L	4	R	1	R	2	R	4	L	1	R	4	R	1	R	8	L	8	R
11	9	R	6	R	2	L	6	L	6	R	6	R	4	L	1	L	6	R	3	R	2	L	3	L	9	R	9	R	2	L	6	L
12	8	L	3	L	8	R	9	L	1	L	4	L	2	R	8	L	5	L	8	L	3	R	4	L	8	L	2	L	2	R	6	L
13	3	L	5	L	8	R	2	L	5	L	8	L	9	R	3	L	1	L	2	L	2	R	9	L	9	L	6	L	1	R	3	L
14	3	R	9	R	3	L	9	R	1	R	9	R	5	L	9	R	6	R	4	R	6	L	4	R	2	R	5	R	3	L	3	R
15	8	R	4	L	3	L	8	R	4	R	4	L	3	L	8	R	9	R	4	L	1	L	4	R	4	R	1	L	4	L	8	R
16	2	R	1	L	4	R	4	R	5	R	1	L	5	R	4	R	2	R	6	L	9	R	3	R	1	R	1	L	3	R	5	R
17	4	L	5	R	8	L	8	L	3	L	3	R	3	L	2	L	4	L	5	R	8	L	1	L	4	L	4	R	8	L	1	L
18	4	L	8	R	1	L	8	L	8	L	2	R	3	L	4	L	8	L	4	R	3	L	5	L	6	L	5	R	4	L	4	L
19	1	L	1	L	9	R	3	R	3	L	1	L	1	R	3	R	3	L	6	L	3	R	2	R	2	L	4	L	4	R	1	R
20	3	R	3	L	4	R	8	R	1	R	2	L	8	R	5	R	3	R	3	L	6	R	8	R	5	R	8	L	1	R	3	R
21	2	R	8	L	8	R	4	L	6	R	2	L	5	R	2	L	4	R	9	L	9	R	8	L	1	R	2	L	9	R	4	L
22	3	L	4	R	9	L	3	L	9	L	4	R	6	L	9	L	3	L	2	R	5	L	3	L	5	L	8	R	1	L	2	L
23	5	R	6	R	6	L	3	L	1	R	9	R	4	L	4	L	5	R	3	R	1	L	2	L	8	R	5	R	2	L	8	L
24	6	R	2	R	2	L	2	R	2	R	4	R	8	L	8	R	2	R	1	R	3	L	3	R	1	R	3	R	6	L	9	R
25	6	L	9	L	1	R	4	R	1	L	5	L	2	R	5	R	6	L	5	L	6	R	6	R	2	L	4	L	3	R	2	R
26	2	R	8	L	3	R	5	R	2	R	6	L	2	R	1	R	4	R	5	L	4	R	2	R	8	R	3	L	5	R	3	R
27	9	R	4	R	5	L	5	L	9	R	9	R	1	L	3	L	5	R	6	R	1	L	6	L	1	R	2	R	1	L	9	L
28	5	L	1	L	6	L	6	L	6	L	3	L	6	L	5	L	8	L	8	L	5	L	1	L	2	L	4	L	3	L	2	L
29	1	L	4	R	5	R	2	R	4	L	5	R	8	R	1	R	2	L	9	R	3	R	8	R	8	L	9	R	9	R	4	R
30	6	L	6	L	1	R	6	L	9	L	3	L	1	R	2	L	2	L	8	L	8	R	6	L	6	L	9	L	6	R	4	L
31	5	R	2	R	5	R	6	R	5	R	5	R	2	R	2	R	8	R	9	R	8	R	1	R	5	R	3	R	9	R	1	R
32	9	R	2	R	5	L	5	L	5	R	3	R	1	L	5	L	9	R	9	R	9	L	1	L	6	R	9	R	5	L	9	L

Appendix 12A. Summary of within-subjects multivariate analysis of variance (MANOVA) for CI scores as a function of the Mode (auditory and visual) and Rate (1.2, 1.6, 2.0, and 2.4 s) of stimulus presentation for Experiment 1.

Source	SS	Df	MS	F	p
Between-Subjects					
Within Cells	1322.49	15	88.17		
Constant	55486.13	1	55486.13	629.34	.001
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	151.49	15	10.10		
Mode	476.63	1	476.63	47.19	.001
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	296.23	45	6.58		
Rate	1826.65	3	608.88	92.50	.001
Within-Subjects (Mode x Rate)					
Within Cells	371.10	45	8.25		
Mode x Rate	24.27	3	8.09	.98	.410

Appendix 12B. Summary of within-subjects MANOVA for CO scores as a function of the Mode (auditory and visual) and Rate (1.2, 1.6, 2.0, and 2.4 s) of stimulus presentation for Experiment 1.

Source	SS	Df	MS	F	p
Between-Subjects					
Within Cells	61.49	15	4.10		
Constant	142.38	1	142.38	34.73	.001
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	27.37	15	1.82		
Mode	.01	1	.01	.00	.949
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	47.23	45	1.05		
Rate	25.40	3	8.47	8.07	.001
Within-Subjects (Mode x Rate)					
Within Cells	43.98	45	.98		
Mode x Rate	11.15	3	3.72	3.80	.016

Appendix 12C. Summary of within-subjects MANOVA for INC scores as a function of the Mode (auditory and visual) and Rate (1.2, 1.6, 2.0, and 2.4 s) of stimulus presentation for Experiment 1.

Source	SS	Df	MS	F	p
Between-Subjects					
Within Cells	196.12	15	13.07		
Constant	465.13	1	465.13	35.57	.001
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	31.75	15	2.12		
Mode	12.50	1	12.50	5.91	.028
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	132.69	45	2.95		
Rate	7.06	3	2.35	.80	.501
Within-Subjects (Mode x Rate)					
Within Cells	78.06	45	1.73		
Mode x Rate	.69	3	.23	.13	.940

Appendix 12D. Summary of within-subjects MANOVA for OM scores as a function of the Mode (auditory and visual) and Rate (1.2, 1.6, 2.0, and 2.4 s) of stimulus presentation for Experiment 1.

Source	SS	Df	MS	F	p
Between-Subjects					
Within Cells	1092.37	15	72.82		
Constant	4950.13	1	4950.13	67.97	.001
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	205.50	15	13.70		
Mode	338.00	1	338.00	24.67	.001
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	187.25	45	4.16		
Rate	1258.25	3	419.42	100.79	.001
Within-Subjects (Mode x Rate)					
Within Cells	234.38	45	5.21		
Mode x Rate	36.13	3	12.04	2.31	.089

Appendix 12E. Summary of within-subjects MANOVA for all Error Types (CO, INC, and OM) as a function of the Mode (auditory and visual) and Rate (1.2, 1.6, 2.0, and 2.4 s) of stimulus presentation for Experiment 1.

Source	SS	Df	MS	F	p
Between-Subjects					
Within Cells	440.83	15	29.39		
Constant	3595.38	1	3595.38	122.34	.001
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	50.50	15	3.37		
Mode	158.88	1	158.88	47.19	.001
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	98.74	45	2.19		
Rate	608.88	3	202.96	92.50	.001
Within-Subjects (Error Type)					
Within Cells	909.16	30	30.13		
Error Type	1962.26	2	981.13	32.37	.001
Within-Subjects (Mode x Rate)					
Within Cells	123.70	45	2.75		
Mode x Rate	8.09	3	2.70	.98	.410
Within-Subjects (Mode x Error Type)					
Within Cells	214.12	30	7.14		
Mode x Error Type	191.63	2	95.82	13.42	.001
Within-Subjects (Rate x Error Type)					
Within Cells	268.42	90	2.98		
Rate x Error Type	681.83	6	113.64	38.10	.001
Within-Subjects (Mode x Rate x Error Type)					
Within Cells	232.71	90	2.59		
Mode x Rate x Error Type	39.87	6	6.64	2.57	.024

Appendix 12F. Summary of within-subjects MANOVA for Successive Blocks of 10 response opportunities (first, second, and third) as a function of the Mode (auditory and visual) and Rate (1.2, 1.6, 2.0, and 2.4 s) of stimulus presentation for Experiment 1.

Source	SS	Df	MS	F	p
Between-Subjects					
Within Cells	440.83	15	29.39		
Constant	18467.63	1	18467.63	628.39	.001
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	51.56	15	3.44		
Mode	164.07	1	164.07	47.73	.001
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	98.49	45	2.19		
Rate	611.55	3	203.85	93.14	.001
Within-Subjects (Blocks of 10 Successive Response Opportunities)					
Within Cells	95.47	30	3.18		
Block	164.44	2	82.22	25.84	.001
Within-Subjects (Mode x Rate)					
Within Cells	123.14	45	2.74		
Mode x Rate	9.07	3	3.02	1.10	.357
Within-Subjects (Mode x Block)					
Within Cells	39.31	30	1.31		
Mode x Block	11.44	2	5.72	4.37	.022
Within-Subjects (Rate x Block)					
Within Cells	131.73	90	1.46		
Rate x Block	18.35	6	3.06	2.09	.062
Within-Subjects (Mode x Rate x Block)					
Within Cells	170.65	90	1.90		
Mode x Rate x Block	17.27	6	2.88	1.52	.181

Appendix 12G. Summary of mixed between-subjects (Sex: male and female) and within-subjects (Mode: auditory and visual; Rate: 1.2, 1.6, 2.0, and 2.4 s) MANOVA for CI scores for Experiment 1.

Source	SS	Df	MS	F	p
Between-Subjects (Sex)					
Within Cells	981.23	14	70.09		
Constant	55486.13	1	55486.13	791.66	.001
Sex	341.26	1	341.26	4.87	.045
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	151.30	14	10.81		
Mode	476.63	1	476.63	44.10	.001
Sex x Mode	.20	1	.20	.02	.895
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	295.58	42	7.04		
Rate	1826.65	3	608.88	86.52	.001
Sex x Rate	.65	3	.22	.03	.993
Within-Subjects (Mode x Rate)					
Within Cells	326.77	42	7.78		
Mode x Rate	24.27	3	8.09	1.04	.385
Sex x Mode x Rate	44.34	3	14.78	1.90	.144

Appendix 12H. Summary of mixed between-subjects (Sex: male and female) and within-subjects (Mode: auditory and visual; Rate: 1.2, 1.6, 2.0, and 2.4 s; Field: left and right) MANOVA for CI scores for Experiment 2.

Source	SS	Df	MS	F	p
Between-Subjects (Sex)					
Within Cells	42713.97	14	3051.00		
Constant	1310164.66	1	1310164.66	429.42	.001
Sex	12064.83	1	12064.83	3.95	.067
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	3567.49	14	254.82		
Mode	562.47	1	562.47	2.21	.160
Sex x Mode	289.68	1	289.68	1.14	.304
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	8401.03	42	200.02		
Rate	40526.11	3	13508.70	67.54	.001
Sex x Rate	715.15	3	238.38	1.19	.324
Within-Subjects (Stimulus Presentation Field)					
Within Cells	1822.32	14	130.17		
Field	33.90	1	33.90	.26	.618
Sex x Field	18.14	1	18.14	.14	.714
Within-Subjects (Mode x Rate)					
Within Cells	5889.65	42	140.23		
Mode x Rate	367.04	3	122.35	.87	.463
Sex x Mode x Rate	33.77	3	11.26	.08	.970
Within-Subjects (Mode x Field)					
Within Cells	2125.54	14	151.82		
Mode x Field	.03	1	.03	.00	.989
Sex x Mode x Field	86.85	1	86.85	.57	.462
Within-Subjects (Rate x Field)					
Within Cells	6119.62	42	145.71		
Rate x Field	990.46	3	330.15	2.27	.095
Sex x Rate x Field	474.59	3	158.20	1.09	.366

continued over...

Appendix 12H cont.

Source	SS	Df	MS	F	p
Within-Subjects (Mode x Rate x Field)					
Within Cells	5794.51	42	137.96		
Mode x Rate x Field	101.00	3	33.67	.24	.865
Sex x Mode x Rate x Field	269.85	3	89.95	.65	.586

Appendix 12I. Summary of mixed between-subjects (Sex: male and female) and within-subjects (Mode: auditory and visual; Rate: 1.2, 1.6, 2.0, and 2.4 s; Order: left-left and right-right) MANOVA for CI scores for Experiment 2.

Source	SS	Df	MS	F	p
Between-Subjects (Sex)					
Within Cells	48528.49	14	3466.32		
Constant	1318823.25	1	1318823.25	380.47	.001
Sex	12364.98	1	12364.98	3.57	.080
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	2065.19	14	147.51		
Mode	.61	1	.61	.00	.950
Sex x Mode	544.10	1	544.10	3.69	.075
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	13535.44	42	322.27		
Rate	44156.60	3	14718.87	45.67	.001
Sex x Rate	1876.71	3	625.57	1.94	.138
Within-Subjects (Stimulus Presentation Order)					
Within Cells	3827.5	14	273.39		
Order	4.19	1	4.19	.02	.903
Sex x Order	3.32	1	3.32	.01	.914
Within-Subjects (Mode x Rate)					
Within Cells	6230.66	42	148.35		
Mode x Rate	1241.35	3	413.78	2.79	.052
Sex x Mode x Rate	59.20	3	19.73	.13	.940
Within-Subjects (Mode x Order)					
Within Cells	2983.16	14	213.08		
Mode x Order	220.34	1	220.34	1.03	.326
Sex x Mode x Order	9.08	1	9.08	.04	.839
Within-Subjects (Rate x Order)					
Within Cells	11292.60	42	268.87		
Rate x Order	871.39	3	290.46	1.08	.368
Sex x Rate x Order	622.76	3	207.59	.77	.516

continued over...

Appendix 12I cont.

Source	SS	Df	MS	F	p
Within-Subjects (Mode x Rate x Order)					
Within Cells	12373.70	42	294.61		
Mode x Rate x Order	266.88	3	88.96	.30	.824
Sex x Mode x Rate x Order	46.87	3	15.62	.05	.984

Appendix 12J. Summary of mixed between-subjects (Sex: male and female; Experiment: 1 and 2) and within-subjects (Mode: auditory and visual; Rate: 1.2, 1.6, 2.0, and 2.4 s) MANOVA comparison of CI scores.

Source	SS	Df	MS	F	p
Between-Subjects (Experiment/Sex)					
Within Cells	2961.95	28	105.78		
Constant	114286.25	1	114286.25	1080.37	.001
Expt.	24.38	1	24.38	.23	.635
Sex	10.97	1	10.97	.10	.750
Expt. x Sex	866.57	1	866.57	8.19	.008
Within-Subjects (Stimulus Presentation Modality)					
Within Cells	312.02	28	11.14		
Mode	358.63	1	358.63	32.18	.001
Expt. x Mode	142.50	1	142.50	12.79	.001
Sex x Mode	4.25	1	4.25	.38	.542
Expt. x Sex x Mode	7.22	1	7.22	.65	.428
Within-Subjects (Stimulus Presentation Rate)					
Within Cells	667.11	84	7.94		
Rate	3611.95	3	1203.98	151.60	.001
Expt. x Rate	.89	3	.30	.04	.990
Sex x Rate	16.92	3	5.64	.71	.549
Expt. x Sex x Rate	16.51	3	5.50	.69	.559
Within-Subjects (Mode x Rate)					
Within Cells	580.55	84	6.91		
Mode x Rate	31.89	3	10.63	1.54	.211
Expt. x Mode x Rate	12.07	3	4.02	.58	.628
Sex x Mode x Rate	27.95	3	9.32	1.35	.264
Expt. x Sex x Mode x Rate	18.42	3	6.14	.89	.451