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Cued shifts of attention and memory encoding in partial report: A dual-task approach

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This study explores how cued shifts of visual attention and rapid encoding of visual information relate to limited-capacity processing mechanisms. Three experiments were conducted placing a partial-report task within a dual-task paradigm. Experiments 1 and 2 involved a simple speeded visual discrimination (Task 1) and then an unspeeded partial-report task (Task 2). Generally, Task 2 accuracy declined as the temporal overlap between the two tasks increased. In addition, in Experiment 1, varying the number of items in the partial-report display had an effect on performance regardless of overlap. In contrast, in Experiment 2, varying the type of probe had an effect only at long task overlap. The generality of the interference effect was tested in Experiment 3 using an auditory discrimination as Task 1. Again, Task 2 accuracy declined as the temporal overlap between the two tasks increased. In all cases, the observed interference had the properties of a processing bottleneck. It is argued that encoding information into memory and response selection for the first task both require general-purpose processing. The results are discussed in terms of the functional relationship between attention and memory.

In the present research, we examined the role of capacity limits in cued shifts of visual attention (cf., Posner, 1980) and the rapid encoding of visual information into short-term memory. Our thesis is that both processes are subject to a processing bottleneck, such as that involved in response selection (e.g., Pashler, 1994). Previous work using dual-task paradigms has investigated capacity limits for these processes separately (Jolicoeur, 1999a; Jolicoeur & Dell'Acqua, 1998; Pashler, 1991). The goal of the present work was to investigate the capacity limits for cued shifts of attention and memory encoding within the same task. In particular, we combined a speeded discrimination task followed by un unspeeded partial report task (e.g., Sperling, 1960). As described later, this combination provides a unique opportunity to

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understand how cued shifts of attention and rapid encoding of visual information relate to central processing limits.

Experimental rationale

In the partial-report task, participants are shown an array of items briefly, followed by a probe that indicates a portion of the array to be reported (Sperling, 1960). In the particular version of partial report we examined here, participants are cued to report a single alphanumeric item adjacent to the position of a subsequently presented visual marker (e.g., Averbach & Coriell, 1961). Partial-report performance requires both shifts of spatial visual attention as well as the encoding and storage of visual information (e.g., Dixon, Gordon, Leung, & Di Lollo, 1997; Giesbrecht & Dixon, 1999; Irwin & Yeomans, 1986; Mewhort, Campbell, Marchetti, & Campbell, 1981). For example, it is commonly held that a great deal of visual information is briefly available after the presentation of the array. Presumably, the presentation of the probe induces a shift of attention to the target location (Dixon et al., 1997). Once attention is directed to that location, selection of some representation of the target stimulus ensues, and the information is encoded and retained in short-term memory for subsequent report (e.g., Coltheart, 1980; Dixon et al., 1997; Irwin & Yeomans, 1986; Mewhort et al., 1981). Much of the research on partial report has focused on the rapid loss of labile information accrued from the brief display. However, in the present research we are concerned with two other aspects of this task—namely, the shift of attention to the probed location and the encoding and retention of the probed information for later report.

In order to understand how shifts of spatial attention and visual encoding relate to bandwidth-limited processing, the partial-report task was placed within the context of a dual-task paradigm. A long-standing issue in the dual-task literature has been what stage (or stages) of processing comprise a processing bottleneck. A widely used paradigm to study this issue is known as the psychological refractory period (PRP) paradigm (for a review see Pashler, 1994). In this paradigm, two simple tasks are to be done at approximately the same time. When the stimulus-onset asynchrony (SOA) between the two tasks is very brief, performance on the second task is very poor; but as the SOA is increased, performance improves (e.g., De Jong, 1993; Jolicoeur & Dell'Acqua, 1998; Pashler, 1994). The pattern of interference observed in PRP experiments is measured in terms of response time and is commonly thought to be diagnostic of the extent to which the two tasks compete for the same processing mechanism. Indeed, a number of results suggest the existence of a processing bottleneck at which second task processing is delayed until the completion of the first (e.g., Pashler, 1994; Pashler, 1998). This approach has been used to determine what stages of processing constitute that bottleneck (e.g., Ivry, Franz, Kingstone, & Johnston, 1998; Johnston, McCann, & Remington, 1995; McCann & Johnston, 1992; Pashler, 1989; Van Selst & Jolicoeur, 1994).

Patterns of dual-task interference can also be observed in tasks where response time on the second task is not the critical dependent measure. De Jong (1993) and Jolicoeur (1998, 1999a) for example, coupled a speeded choice reaction time task (Task 1) with an unspeeded discrimination task (Task 2). As in the PRP paradigm, when the Task 1–Task 2 SOA is brief the performance on Task 2 is very poor, as measured by discrimination accuracy, and improves as the SOA between the tasks is increased. We adopt a similar approach, combining a speeded discrimination task with an unspeeded partial-report task in order to examine how the attentional and encoding mechanisms involved in the partial-report task are related to central bandwidth-limited processing.

Several studies have used a dual-task approach to investigate how memory encoding and spatial attention relate to central attentional mechanisms (e.g., Johnston et al., 1995; Jolicoeur & Dell'Acqua, 1998, 1999; Pashler, 1991). For instance, Jolicoeur and Dell'Acqua (1998,1999) have investigated the relationship between memory encoding mechanisms and bandwidth-limited mechanisms (see also Jolicoeur, 1999a). In one experiment (Jolicoeur & Dell'Acqua, 1998), participants were presented with either 1 or 3 characters (letters or digits) followed by a mask. After an interval ranging from 350–1,600 ms, a tone was presented, and participants were to indicate as quickly and as accurately as possible whether the tone was high or low in pitch. At the end of the trial, participants were asked to report the string of characters only if they were letters, without time pressure. When the string was letters, response times to the tone task were prolonged at short SOAs between the two tasks and decreased in duration as the SOA increased. Moreover, this pattern of interference was considerably more severe when participants had to encode three letters compared to only one letter. In contrast, Jolicoeur and Dell'Acqua observed only minimal interference when the string consisted of digits. Based on these and other results, Jolicoeur and Dell'Acqua argued that the process of encoding information into short-term memory requires access to the same central mechanism as does response selection in the speeded tone task. They identified this mechanism as one of short-term memory consolidation.

Related to this research, Pashler (1991) investigated how shifts of visual attention relate to general processing. In one experiment, participants performed a tone discrimination task followed by an unspeeded bar-probe partial-report task. In the second task, two rows of letters, drawn from the set A, B, C, and D, were presented, followed by a pattern mask of Xs. The probe consisted of a horizontal bar that appeared either below a letter on the bottom row or above a letter on the top row. The task was to respond as quickly and accurately as possible to the tone and then to identify the probed letter without time pressure. Generally, Pashler found little interference as a function of the SOA between the two tasks, despite the fact that performance suffered substantially if the probe was delayed a few hundred milliseconds. Moreover, when a speeded task was used as the second task dual-task interference was observed, but the patterns of interference indicated that shifts of spatial attention could be executed independently of response selection. Consequently, Pashler concluded that shifts of spatial attention based on the probe do not require the same limited-capacity mechanisms as those required for response selection in the first task.

More recently, Johnston and his colleagues (Johnston et al., 1995) reported two experiments designed to identify the relationship between spatial attention and central processing mechanisms. In both experiments, subjects identified a visually distorted letter. In the first experiment, the letter identification task was used as the second task in psychological refractory period paradigm (e.g., Welford, 1980) to measure central attentional mechanisms; in the second experiment, the letter identification task was used in a spatial cueing paradigm (e.g., Posner, 1980) to measure spatial attentional mechanisms. The distortion of the letter was manipulated to make its identification either easy or difficult. In both experiments, effects of the putative attention mechanisms were obtained (i.e., dual-task slowing in Experiment 1 and faster response times at the cued location than at the uncued location in Experiment 2). However, the critical result of the first experiment was that the effect of letter distortion was observed only at long inter-task intervals. Drawing on the logic of bottleneck models of dual-task interference (for detailed reviews see Pashler, 1994, 1998), Johnston and colleagues concluded from this interaction that letter identification must occur prior to the central limitations of response selection. In contrast, in the second experiment, the manipulation of letter distortion was additive with the measure of spatial attention, suggesting that letter identification occurs after shifts of spatial attention. Thus, putting the results of both experiments together, Johnston and his colleagues concluded that shifts of spatial attention occur prior to letter identification, which, in turn, is prior to more general bandwidth-limited processing.

In combination, these patterns of interference suggest that shifts of spatial attention are distinct from encoding into short-term memory: The Jolicoeur and Dell'Acqua (1998) effects suggest that short-term memory consolidation requires central processing (see also Jolicoeur, 1999a); Pashler's (1991) results suggest that shifts of attention can be executed in parallel with central processing; finally, the results of Johnston et al. (1995) suggest that shifts of spatial attention are executed prior to bandwidth-limited processing. However, none of these experiments addresses the relationship between attentional shifts and short-term memory directly. Because Jolicoeur and Dell'Acqua asked participants to report all of the briefly presented items, it seems likely that no shifts of spatial attention were required. In Pashler's partial-report task, the small arrays and limited population of stimulus items may have minimized the demand on short-term memory and the need to use encoding operations such as short-term memory consolidation. Finally, the conclusions of Johnston et al. were based on the results from two very different paradigms. The present paradigm was designed to involve both attentional shifts and short-term memory encoding in the same task in order to further our understanding of their relationship.

The present approach

We report three experiments using the partial-report task as the second task within a dual-task paradigm. The partial-report task was similar to that of Dixon et al. (1997). The display consisted of a circle of letters, centred on fixation. The letters were presented very briefly and then followed by a bar probe indicating the to-be-reported letter. In separate experiments, we systematically manipulated the quality of the information in the display or the attentional component in the bar-probe task. The hypothesis was that if the manipulations result in similar patterns of interference, then the two components probably require access to similar mechanisms and perhaps occur at the same stage of processing. If, however, the patterns of interference are different, then the two components probably do not require similar mechanisms and do not occur at the same stage of processing. To anticipate our findings, the results support the view that shifting attention in the partial-report task does not require the same information processing mechanism(s) as does short-term memory encoding and is likely to occur at an earlier stage of processing.

GENERAL METHOD

Stimuli

The stimuli were presented dark-on-light on a 33-cm Apple RGB video monitor. First-task stimuli were the digits 8 and 4; second-task stimuli consisted of upper-case letters from the English alphabet. Masking stimuli for the second task were #s. All stimuli were presented in 18-point Times font. Viewing distance was approximately 50 cm. At this distance the alphanumeric stimuli subtended approximately 0.69° vertically.

For the first task, the digit was presented at fixation. For the second task, letters were evenly distributed on the perimeter of a notional circle with a radius of approximately 1.65° of visual angle. Letters presented in the partial-report display were selected randomly without replacement. Unless mentioned otherwise, the probe was a radial line that started 1.1° from the centre of the circle, was 0.33° in length, and terminated approximately 0.22° from the centre of the target letter. The position of the partial-report target was randomly determined on each trial.

Procedure

At the beginning of the session, participants were given a written and then an oral explanation of the events on each trial. Participants were told that on each trial there were two tasks: The first was a speeded digit discrimination task, and the second was an unspeeded partial-report task. The experimenter stressed the importance of giving priority to the first task and doing it as quickly and accurately as possible. Participants were told that the second task consisted of a circle of letter, presented very briefly, and that the task was to identify the letter presented in the location indicated by a bar probe. Identification was to be as accurate as possible with no time pressure.

After the tasks were outlined, the lighting in the room was dimmed, and participants were seated in front of the monitor. Participants held a button box in both hands, positioning their left thumb over a button marked “4” and their right thumb over a button marked “8”. This response mapping was the same for all participants. At the beginning of each trial, a small fixation dot appeared in the centre of the screen, indicating where the Task 1 digit would be presented as well as the centre of the notional circle for Task 2. Participants were told to fixate the centre of the screen for the duration of the trial. Once fixated, participants initiated each trial by pressing “4” and “8” buttons simultaneously. After a 495-ms delay, the dot was replaced by the number 4 or 8. The digit was displayed for 30 ms and was not masked. Participants were instructed to indicate the identity of the digit by pressing either the “4” button with their left thumb or the “8” button with their right thumb.

The stimuli for the second task followed the first-task stimulus at a variable SOA. The partial-report array was presented for 30 ms. Coincident with the offset of the letters, the probe was presented for 30 ms. After a blank interval of 60 ms, the letters were masked by a circle of #s for 30 ms. Participants gave their response to the second task by using a computer mouse to select one of five alternatives that were displayed on the screen at the end of each trial. The five alternatives consisted of the target, the two letters that were adjacent to the target in the display, and two letters that did not appear in the display. The alternatives remained on the screen until a response was made.

At the end of each trial, participants were given feedback on their Task 1 response: If the response was correct, participants were given their response time; if they were incorrect, the words “BUTTON ERROR” were displayed for 495 ms. After the feedback, the fixation dot reappeared to indicate that the next trial was ready to begin. The sequence of events for a typical trial is illustrated in Figure 1.

The importance of several aspects of the study were stressed to the participants. First, due to the brief display durations and the fact that the second task was not at fixation, but centred around fixation, the experimenter stressed the importance of maintaining fixation on the centre of the screen. Second, priority was to be given to the first task. To help participants in this regard, they were told that with practice, their response times could be consistently less than 400 ms. Third, participants were discouraged from withholding their first response until the second display was presented. Performance was monitored during the practice blocks in an attempt to prevent this strategy of conjoint responding (Pashler & Johnston, 1989).

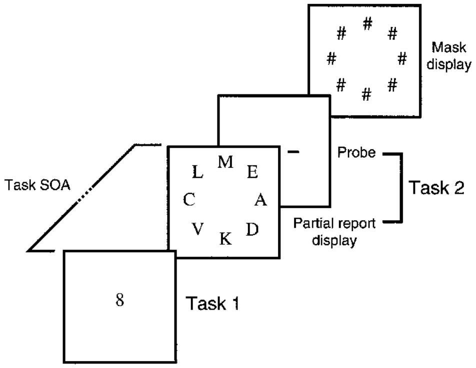

Figure 1. A sample display sequence. The Task 1 digit is presented centrally for 30 ms. After a variable stimulus onset asynchrony (SOA) the Task 2 partial-report display is shown for 30 ms, immediately followed by the probe. The mask display is presented 120 ms after the onset of the partial-report display. Participants are required to make a speeded on-line digit discrimination for the first task. At the end of the trial, participants report the identity of the target letter ("A" in the figure) under no time pressure.

EXPERIMENT 1

In Experiment 1, we examined the effects of the quality of information provided in the partial-report task by presenting an array containing either 8 or 12 items. This manipulation is analogous to that used by Jolicoeur and Dell'Acqua (1998) in which either 1 or 3 items were presented for report. However, as we will discuss later, this analogy is merely superficial because the interpretation of effects of array size is somewhat different in partial report (where participants report only a single item) then in the whole-report task used by Jolicoeur and Dell'Acqua. The critical point to note is that we hypothesize that increasing the array size decreases the quality of the information that can be encoded in short-term memory while leaving other aspects of selection and encoding intact.

Encoding information into short-term memory (also called durable storage, Coltheart, 1980) is thought to be required for partial report (e.g., Averbach & Coriell, 1961; Coltheart, 1980; Sperling, 1960). Presumably, this encoding entails a consolidation process akin to that assumed by Jolicoeur and Dell'Acqua (1998) in their explanation of the dual-task interference that they observed. In particular, they argued that the process of consolidating information from the second task requires access to central processing that is also required for selection of the response in the first task. Thus, while response selection for the first task is being completed, the consolidation must wait. During this delay, the representation of the second-task display is degraded by the subsequent pattern mask, thereby impairing performance (Giesbrecht & Di Lollo, 1998; see also Jolicoeur & Dell'Acqua, 1998). Short-term consolidation should also be required in a partial-report task. Thus, on this analysis, when a partial-report task is the second task within a dual-task paradigm, performance on that task should be poor at short SOAs and improve as the SOA between the tasks is increased.

As Jolicoeur and Dell'Acqua (1998) have demonstrated, increasing the number of items in a whole-report display affects late encoding mechanisms that compete for limited bandwidth mechanisms that are also required for response selection. However, increasing the number of items in a partial-report display, were only a single item is to be reported, can have an earlier locus of effect. Recently, we demonstrated that reducing the inter-item distance in a partial-report display reduces accuracy of report (Giesbrecht & Dixon, 1999). Reducing the inter-item distance increases the likelihood for local contour interactions and lateral masking (e.g., Wolford, 1975). Moreover, the effect of increasing the number of items in the display when inter-item distance was controlled was very small (2%). Thus, it seems likely that inter-item distance has an early locus of effect, such that reducing inter-item distance reduces the quality of the representation of the selected and encoded information.

The critical manipulation in Experiment 1 was the number of items that appeared in the partial-report display. For half the trials there were 8 letters in the display, and for half the trials there were 12. The radius of the circular array of items was the same for the two types of trial, so that the inter-item distance was substantially smaller with the 12-item displays. There were two predictions. First, based on the notion that memory encoding requires access to a general-purpose mechanism that is also required for response selection of the first task, the prediction was that dual-task interference should be observed in terms of reduced performance on the second task. Second, based on the notion that decreasing inter-item distance affects the quality of the representation, but not selection and encoding, the observed effect of inter-item distance should be more severe when there are more items in the partial-report display, and it should be approximately additive with SOA.

Method

Participants

A total of 15 undergraduates (10 female) from the University of Alberta subject pool participated for class credit (age range: 18–21 years). All were right handed and all reported having normal or corrected-to-normal vision.

Stimuli

As mentioned in the General Method, the letters in the partial-report display were distributed evenly on the perimeter of the notional circle. Consequently, in the 8-item condition the distance between the centres of each letter was 1.30° of visual angle, whereas the distance was 0.86° of visual angle in the 12-item condition.

Design

The experiment consisted of a single one-hour session. The session was split in half, where the halves differed only in the number of items in the partial-report task. In one half, Task 2 consisted of 8 letters; in the other, Task 2 consisted of 12 letters. The order of presentation of the item conditions was counterbalanced across subjects. Each item condition consisted of eight blocks of trials, the first two being practice blocks. In each block, the SOA between the two tasks was mixed randomly and was 60, 120, 240, or 480 ms. In each block there were 4 trials in each SOA condition, resulting in 16 trials per block. Between each block, participants were given an opportunity to rest. The design resulted in 32 practice trials and 96 experimental trials per item condition.

Results

Five participants were excluded from the analyses. One participant failed to comply with the task instructions, and four had difficulty with the second task, with the mean level of accuracy in at least one cell being less than 15%. The remaining 10 participants were included in all analyses[1].

Task 2 accuracy. In this and subsequent experiments, estimates of Task 2 identification were based on those trials in which the response to the first task was correct. These data, averaged over subjects, are shown in Figure 2 as a function of the number of items in the display and SOA. Error bars in this and subsequent figures are 95% confidence intervals appropriate for within-subject pairwise comparisons, calculated based on the procedure described by Loftus and Masson (1994). The overall SOA effect was such that identification accuracy was the lowest (44.9%) in the 60-ms SOA condition and improved to an asymptotic level of 59% in the 240-ms SOA condition. Identification accuracy was higher in the 8-item condition (57.4%) than in the 12-item condition (46%); however, the temporal course of the SOA effect did not change as a function of the number of items in the display.

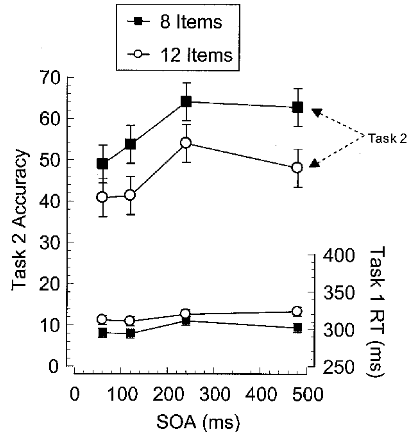

Figure 2. Results of Experiment 1. The upper portion of the figure illustrates the mean percentages of correct identification of the partial-report target, given accurate identification of the Task 1 digit. The lower portion of the figure illustrates the mean response times (RT) for Task 1 for accurate trials only. Error bars represent 95% confidence intervals and are appropriate for within-subjects pairwise comparisons (Loftus & Masson, 1994).

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[1] Using these exclusion criteria 16 of the 48 subjects who participated in Experiments 1–3 were excluded from the analyses. It might be argued that excluding such a large number of subjects may have biased the results; however, there are several reasons why we believe that this is not the case. First, as is clear from the generally low level of performance of the included subjects, the partial-report task was very difficult. Indeed, 50% of the excluded subjects were excluded because of chance performance on the second task. As most of these subjects had difficulty on the second task at the shortest SOAs, inclusion of these subjects is likely to bias the results in favour of an effect of SOA. In addition, 25% of the excluded subjects were excluded because of high error rates on the first task, rendering their response times uninterpretable. Thus, omitting the subjects is the more conservative approach.

In order to assess the strength of evidence provided by these results, a set of linear models were fitted to the data, and their relative adequacy was measured using maximum-likelihood ratios (Cohen, 1994; Dixon & O'Reilly, 1999; Loftus, 1993). The likelihood ratio is the likelihood of the data given one model divided by the likelihood of the data given another. If the observed main effects and interactions in the data are independent of one another, the likelihood of the data corresponds to the product of the likelihoods for each of the observed effects. (This corresponds to the usual practice in the analysis of variance of testing each effect separately and is a conservative approach when the error variance may not be homogeneous.) Likelihoods are inversely proportional to the residual error in a model, and the ratio of two likelihoods is closely related to the sum of square calculation in analysis of variance. It can be shown that in a repeated measures design, the likelihood ratio, λ, for comparing a model that includes an effect A with an identical model that does not include that effect is:

$$\lambda = \left(\frac{SS_A + SS_{AS}}{SS_{AS}} \right)^{s(c-1)/2}$$

where SS_A is the sum of squares for the effect, SS_{AS} is the sum squares for the interaction with the subjects, s is the number of subjects, and $c - 1$ is the degrees of freedom associated with the effect.

In many situations, evaluating the likelihood ratio is similar to testing null hypotheses, and in some prototypical hypothesis-testing applications, obtaining a likelihood ratio of 10 or greater corresponds approximately to rejecting the null hypothesis with $\alpha < .05$ (Dixon, 1998). Thus, as a heuristic, we interpret likelihood ratios of 10 or greater as constituting clear evidence in favour of one model over the other.

Using likelihood ratios to evaluate models in this way provides precisely the same information as that found in most applications of analysis of variance. Indeed, in all of the cases reported later that have a likelihood ratio greater than 10, there is a corresponding analysis of variance effect or interaction with a p value smaller than .05 (the results of traditional hypothesis tests are summarized in the Appendix). However, the likelihood ratio merely summarizes the evidence obtained in the results; it does not entail a decision to reject a null hypothesis. As a consequence, it is immune to the logical problems involved in significance testing (e.g., Dixon & O'Reilly, 1999; Goodman & Royall, 1988).

To evaluate the effects of SOA and array size on partial-report performance, a series of nested linear models were compared; conceptually, these correspond to the effects and interactions that would be tested in an analysis of variance. The first model is a null model in which it is assumed that all conditions yield equivalent performance. This was compared to an SOA-only model incorporating the assumption that performance increased monotonically as a function of SOA. The likelihood ratio comparing these two models was $\lambda > 1{,}000$. In other words, the data are more than 1,000 times as likely on the assumption that SOA has an effect on performance. Third, the SOA model was compared to an additive model incorporating effects of both SOA and array size. The likelihood ratio for this comparison was also greater than 1,000. Thus, there is strong evidence for an effect of array size in addition to the effect of SOA alone. Finally, the additive model was compared to a full model that also included the interaction between SOA and array size. This yielded $\lambda = 2.22$. This value is substantially below the criterion of 10 for clear evidence in favour of a model, and it suggests that there is little evidence for an interaction between SOA and array size.

Task 2 errors. In this partial-report task, errors can be of two types: intrusions or transpositions. Intrusion errors are those identifying a letter that was not in the display as a target. Transposition errors are those identifying a letter that was in the display, but that was not the target. In this and subsequent experiments, estimates of transpositions were based on those trials in which an error was made. Overall, 60.8% of errors were transposition errors. The percentage of transpositions increased as a function of SOA. The percentages of transpositions in the 60, 120, 240, and 480-ms SOA conditions were 57.2, 56.0, 62.8, and 67.4, respectively. Transpositions were the same in the 8- and 12-item conditions (60.2% vs. 61.4%), and the temporal course of the SOA effect did not change as a function of the number of items in the display.

Task 1 response time. Only those response times from correct trials were included in the analysis. Median response times in each cell for each subject were averaged across subjects and are shown in Figure 2. The overall mean response time was 308 ms. There was a small increase in response time as the SOA between the two tasks increased. The largest difference in response time was between the 120-ms SOA and the 180-ms SOA conditions, where mean response times were 302 ms and 315 ms, respectively. Response time did not change as a function of the number of items in the display, where the mean response time was 308 ms in the 8-item condition and 313 ms in the 12-item condition. There was also no interaction between the number of items and SOA; response times increased modestly in each letter condition, but the increase over SOA was the same.

Task 1 errors. The error rate collapsed across all conditions was 7.9%. The error rate did not change as a function of the SOA between Task 1 and Task 2. There was also no change in error rate as a function of the number of items in the partial-report display (8-letter mean = 8.0%; 12-letter mean = 7.8%). There was a slight trend in the error data such that in the 8-item condition the error rate was 12.1% at the shortest SOA, whereas in the 12-item condition the error rate was 5% at the shortest SOA.

Discussion

There were two main results in Experiment 1. First, performing a visual choice reaction time task interfered with doing a partial-report task. The nature of the interference was such that Task 2 performance was low when the SOA between the two tasks was brief and improved as SOA increased. Second, there was an approximately additive effect of the number of items in the display, with performance in the 8-letter condition being better than that in the 12-letter condition.

The source of dual-task interference in the partial-report task is suggested by the recent work of Jolicoeur and Dell'Acqua (Jolicoeur, 1999a; Jolicoeur & Dell'Acqua, 1998, 1999). They argue that the mechanism responsible for choosing a response for their speeded Task 1 is also required to consolidate information into durable storage for Task 2. Thus, the common mechanism represents a processing bottleneck. Their model also provides a plausible account of the interference observed in the present study, on the assumption that the information selected on the basis of the partial-report cue needs to be consolidated in short-term memory, just as does the entire array of items in the Jolicoeur and Dell'Acqua task. When the SOA is short, the mechanism required for this consolidation of the partial-report information is engaged in choosing a response for the first task. Under these circumstances, the consolidation of the selected information is delayed until response selection for the first task is complete. During this delay the representation of the partial-report display remains in a state that is labile and vulnerable to masking (e.g., Giesbrecht & Di Lollo, 1998; Jolicoeur, 1999a). Consequently, performance should improve with increasing SOA.

What is of greatest importance for the present purpose is the absence of a strong interaction between the number of letters in the display and SOA. In dual-task experiments where the dependent measure is response time, an additive pattern over SOA suggests that the difficulty manipulation affects a stage of processing that requires limited bandwidth processing, which is also required for choosing a response for Task 1 (e.g., Pashler, 1994). The logic behind this conclusion is based on the assumptions of so-called bottleneck models of dual-task interference (Pashler, 1994, 1998; Welford, 1980). In these models, it is assumed that some of the operations involved in task performance can be executed in parallel whereas others require the exclusive dedication of a certain processing mechanism(s). If processing in the second task proceeds to the point where it requires the use of a mechanism at a time when it is still engaged in Task 1 processing, then Task 2 processing is postponed until after the mechanism has become available. In these models, the shared mechanism is said to represent a processing bottleneck. These models predict that if stages of Task 2 at or after the bottleneck stage are made more difficult, there should be a constant effect on performance on Task 2 that is additive with the effect of SOA between the two tasks (Pashler, 1994).

Applying bottleneck logic to the additivity of SOA and the number of items implies that the items manipulation —which we argue is a stimulus quality manipulation—has its effect at a limited-capacity stage. However, several previous dual-task studies have manipulated stimulus quality through other means (e.g., letter distortion, Johnston et al., 1995; contrast/intensity, Pashler & Johnston, 1989) and found that such manipulations interact with SOA in a manner implying that the locus of effect is prior to the bottleneck stage (e.g., Pashler, 1994). The discrepancy between our results and those of previous dual-task studies reflects important differences between our task, which uses accuracy as the dependent measure, and traditional PRP experiments, which use response time as the dependent measure. Perhaps the most important difference is that our manipulation is a data limitation: It does not matter how long or hard one works at identifying the letters, there is just less information available in the large arrays presented under these conditions. On this analysis, array size should have an effect on accuracy even under unspeeded, single-task conditions. As mentioned in the Introduction, we recently demonstrated that this is indeed true (Giesbrecht & Dixon, 1999). In contrast, stimulus quality manipulations, such as those used in more traditional RT experiments, are not typically data limitations: They can be "cleaned up" with a little extra work. This is indicated by increased response time with little or no associated decrease in accuracy under single-task conditions (e.g., Pashler, 1984) and reduced effects of quality manipulations at short task SOAs in dual-task conditions (i.e., an underadditive interaction, Johnston et al., 1995; Pashler & Johnston, 1989).

As a consequence of this fundamental difference, our interpretation of the approximate additivity of SOA and the number of items in our tasks, where the dependent measure is accuracy, is somewhat different from the interpretation when response time is the dependent measure. As outlined earlier, we assume that increasing the number of items decreases the quality of the representation of the information that needs to be selected and encoded into usable storage, regardless of the SOA between T1 and T2. At short SOAs, encoding is delayed because response selection for T1 is unlikely to be complete. When encoding does occur, the quality of this information is lower when there are more items in the display. At long SOAs, despite the fact that encoding can usually occur as soon as the probe is presented, the quality of the representation is still lower when there are more items in the display. Thus, there are two sources of interference in the present experiment that combine to produce the observed pattern of results: An early effect of inter-item distance that affects the quality of the visual representation and a later effect of SOA that delays consolidation of the partial report target into durable storage.

Figure 3 provides a depiction of this interpretation. The grey and hatched bars represent information about the partial-report target selected on the basis of the bar probe. We assume that shortly after the probe is presented, attention shifts to the probed location and information at and in the vicinity of the target is selected. However, we assume that this selected information is maskable and that if it is not consolidated in short-term memory it is degraded or lost when the mask is presented. Consequently, in Figure 3 the maskable information, shown as the grey bar, is depicted as having an offset 120 ms after the onset of the array. We also assume, though, that the mask does not completely eliminate all of the target-relevant information and that some residual information will persist for a relatively long period of time even after the mask. This residual information probably consists primarily of a few isolated features or line segments (cf., Prinzmetal, 1992). The residual information is indicated in the figure by the long, hatched bar extending past 120 ms. As suggested earlier, partial-report performance depends on being able to consolidate information about the target in short-term memory, and the earlier this consolidation can take place, the more likely the participant will be able to use of the bulk of the selected information available prior to 120 ms. However, this consolidation is potentially delayed by the need to use the same central mechanism for selecting the response in Task 1. This constraint is indicated in Figure 3 by the curve representing the probability of response selection being completed at various times after the start of the trial. When the completion time is early (relative to the array presentation in Task 2), the selected information can be consolidated prior to the onset of the mask; when the completion time is longer, only the residual information is available, and performance suffers. The upper panel depicts the hypothesized situation at short SOAs; here, response selection will rarely be finished prior to the presentation of the mask, and performance on most trials must rely on only the residual (non-maskable) information. The lower panel depicts the situation with longer SOAs; in this case, response selection is more likely to finish prior to the presentation of the mask, and more trials can make use of the maskable information. Thus, partial-report performance should improve with increasing SOA.

We assume that the number of items in the array has an effect on the nature of the selected information. For example, Giesbrecht and Dixon (1999) argued that decreasing the spacing between items in partial report increases the opportunity for feature migrations or item transpositions leading to lower accuracy (see also Irwin & Yeomans, 1986; Wolford, 1975). On this

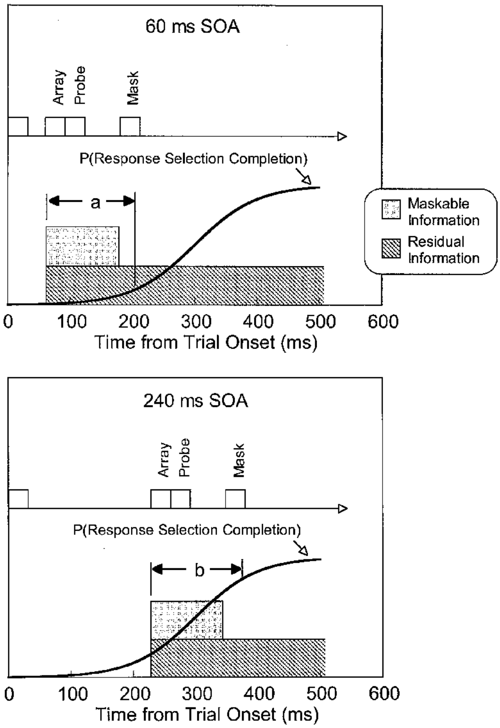

Figure 3. A conceptual diagram outlining the fate of the partial-report information. The grey and hatched bars represent information about the partial-report target. The probability density represents the time at which response selection for the first task is completed. Prior to the onset of the mask, the amount of information regarding the target is relatively high, but is reduced by the mask. Thus, if response selection of the first task overlaps with the partial-report display and delays encoding of the target into memory, then only residual information about the target will remain by the time response selection is complete. However, if there is little or no overlap with response selection (i.e., the probability density is shifted to the right), then encoding into memory is based on more than merely residual information. The maskable information is depicted by the grey bar; the residual information is depicted by the hatched bar.

hypothesis, we assume that decreasing the spacing between items in the display reduces the quality of the residual information, which contributes to accuracy regardless of SOA. Thus, the effect on accuracy is independent of the interference caused by delaying short-term consolidation, and consequently an effect on accuracy is found at all SOAs, as shown in Figure 2.

The explanation that the source of interference is due to a failure to encode information into durable storage complements the traditional interpretation of probe-delay effects in partial-report experiments. A standard result in partial report is that performance declines markedly with increased delay of the probe (e.g., Sperling, 1960). As with the interference effects observed in the present experiments, this decline in performance is held to reflect the degradation of information due to decay or masking before it can be consolidated into short-term memory (e.g., Averbach & Coriell, 1961; Sperling, 1963). This parallels our account of dual-task interference obtained with decreasing SOA found here. However, in a traditional partial-report task, delaying the probe delays both the selection of information from the array as well as its consolidation. Unfortunately, the results of the present experiment do not allow us to draw conclusions regarding when selection of information from the array occurs (i.e., whether it occurs at the onset of the probe or just prior to consolidation). Nevertheless, our results do provide evidence that converges the work of Jolicoeur and his colleagues (Jolicoeur, 1998, 1999a; Jolicoeur & Dell'Acqua, 1998, 1999; Ross & Jolicoeur, 1999), supporting the notion that the consolidation of information from the array is delayed by the requirements of response selection in a temporally preceding task. Adopting this assumption forces the prediction that there should be trial-to-trial dependencies between performance in the partial report task and response time in digit discrimination task.

It follows from our interpretation that the critical variable determining the amount of interference is the delay in accessing the central mechanism responsible for short-term consolidation, rather than SOA per se. In particular, SOA measures the difference in time between the beginning of Task 1 and the beginning of Task 2. However, the central bottleneck mechanism is required for response selection in Task 1, and response selection occurs near the end of Task 1 rather than the beginning. As a consequence, we believe that the end of Task 1 is a better index of when the central mechanism is free to do short-term consolidation in Task 2. We refer to the time from the onset of Task 2 to the response for Task 1 as *task overlap*. Formally, task overlap is calculated as Task 1 response time minus SOA. Consequently, the interference effects that occur at short SOAs would be apparent at long task overlap. A similar logic has been used in examination of interference as a function of Task 1 reaction time by Pashler (1991) and Jolicoeur et al. (Jolicoeur, 1998, 1999a; Jolicoeur & Dell'Acqua, 1998, 1999; Ross & Jolicoeur, 1999).

Task overlap provides a more accurate index of the time at which the central bottleneck becomes free whenever the variability in processing time preceding response selection is greater than that after response selection. This is illustrated in Figure 3. The arrow marked "a" in the upper panel indicates the delay in accessing the central mechanism on a short SOA trial when the Task 1 response time is fast. In this case, response selection would also be expected to be finished quickly, and the delay would be determined by the left-hand edge of the completion time distribution. In this example, the delay would be about 200 ms. The hatched arrow labelled "b" in the lower panel depicts what would happen on a long-SOA trial with a slow response. Assuming that the slow response time is due to extended encoding and decision operations, one would also expect response selection to be slower in this case. Thus, arrow "b" indicates the delay that would occur when completion time comes from the right-hand edge of the distribution, and again the delay would also be about 200 ms in this example. If the delay in short-term consolidation were indexed only by SOA, the actual delay would be overestimated in the trial in the upper portion of Figure 3 and underestimated in the bottom portion. However, much less error would occur using overlap time, calculated by subtracting SOA from response time. This calculation of overlap was completed for each subject in each array size condition. This distribution of overlap times was divided into eight bins in each condition, and the mean overlap time and partial-report accuracy for each of these bins were calculated. One caveat about the overlap analysis must be noted: Although calculating task overlap in this manner has the advantage of placing effects of SOA and Task 1 processing time on the same function, it does not allow one to evaluate the independent effects of SOA and Task 1 processing time.

Figure 4 shows the results. Generally, the interference effects based on estimated overlap show the same pattern as that found in Figure 2; however, the effects are stronger, as expected

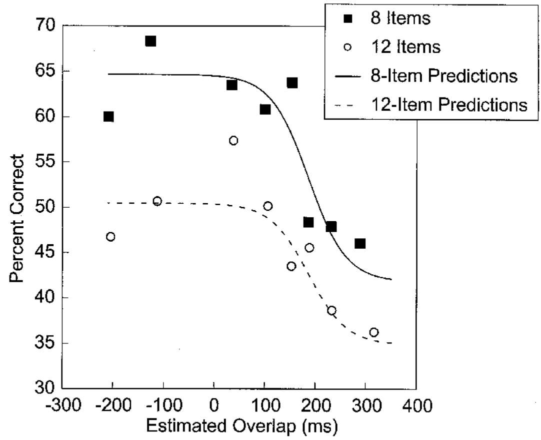

Figure 4. Results of the overlap analysis of Experiment 1. Symbols represent observed data; curves represent the model predictions.

on the present logic. What is readily apparent from the figure is that when there is little overlap, performance is high, but that performance gradually declines as overlap increases, reaching asymptotic levels in the vicinity of 200 ms. As before, there is a relatively constant difference between the 8-letter and 12-letter conditions across all SOAs, even when overlap is substantial. The decline in performance as a function of increasing task overlap supports the notion that encoding information into short-term memory in a partial-report task requires access to mechanisms that are also required for response selection of Task 1 (see also Jolicoeur, 1998, 1999a; Jolicoeur & Dell'Acqua, 1998, 1999; Ross & Jolicoeur, 1999, who also demonstrate a similar negative relationship between response time for a speeded Task 1 and accuracy on an unspeeded Task 2).

In order to demonstrate more explicitly how our interpretation matches the obtained results, we fitted a simple mathematical model to the data shown in Figure 4. In this model, we assumed that the bulk of the information was available from the onset of the cue to the onset of the mask, and that only residual information was available thereafter. Further, we assumed that this information would be consolidated in short-term memory as soon as the central bottleneck was free after selecting the response in Task 1. For computational convenience, the distribution of completion times for Task 1 response selection was modelled as a logistic distribution centred at a fixed time prior to the end of Task 1. Following our analysis of the effect of array size described earlier, we assumed that increasing the number of items in the array decreased the information that could be consolidated by a constant proportion, regardless of whether it came from the unmasked or residual components. This model required five parameters: the amount of maskable information (s), the amount of residual information following the mask presentation (r), the mean and standard deviation of the completion time distribution (μ, σ), and the proportional decrement with 12 instead of 8 items (j). In addition, there was a fixed parameter (g) for the probability of guessing the correct answer when there is no available information; g was set to 0.2. Proportion correct for a given overlap time t is thus:

TABLE 1
Estimated parameter values

	Experiment		
Parameter	*1*	*2*	*3*
s	0.286	0.286	0.286
r	0.273	0.273	0.273
μ	187	187	446
σ	37	37	37
j	0.682	0.682	
k		0.120	

$$P(C) = g + (1-g)\left\{ r + \frac{s}{1+\exp[(t-\mu)/\sigma]} \right\}$$

when there are 8 items in the array and

$$P(C) = g + (1-g)\left\{ jr + \frac{js}{1+\exp[(t-\mu)/\sigma]} \right\}$$

when there are 12 items.

Maximum likelihood estimates of the parameters were generated using a gradient descent algorithm on the assumption that the observed mean proportion correct was sampled from a binomial distribution; these values are shown in Table 1. Similar models were fitted to the results of Experiments 2 and 3, as is discussed later; except as noted, the parameter values were constrained to have the same values in all three fits. The predictions for percentage correct are shown as continuous lines in Figure 4. The model provides an accurate account of the main features of the data, including the decline in accuracy with increased overlap, and the approximately additive effects of array size. There is a tendency, not captured by the model, for accuracy to decline with long, negative overlap times. These negative overlap times occur with SOAs that are substantially longer than the Task 1 response time. We suspect that under these circumstances, partial report performance may suffer because of temporal uncertainty concerning the array presentation: Participants may simply not be as ready for the brief array presentation when there is a relatively long delay between tasks as they are when the stimuli come in more rapid sequence.

EXPERIMENT 2

The purpose of Experiment 2 was to investigate the mechanism of shifting spatial attention in the bar-probe task. In particular, if shifts of attention are executed less effectively or efficiently, then the amount of target information available prior to the mask should decrease, and, as a consequence, there should be less interference due to delaying the short-term consolidation process. In order to test this hypothesis, we used partial-report probes that were either peripheral (near the target) or central (at fixation). Shifts of attention to a peripheral stimulus are thought to be fast, whereas shifts of attention induced by a central stimulus are thought to be slow (Dixon et al., 1997; Jonides, 1981; Müller & Rabbitt, 1989). We hypothesize that the slower shifts of attention based on a central probe would be less effective in selecting the information concerning fine spatial alignment of visual features (i.e., maskable information in Figure 3); as a consequence, performance should suffer. However, this decrement in performance should only be observed when short-term consolidation occurs prior to the mask; after the mask, only residual information about isolated visual features would be available, regardless of whether the initial shift of attention was fast or slow. A similar manipulation was used in Experiment 5 of Pashler (1991). However, his results do not bear on the predicted interaction because very little interference was observed in any conditions.

Method

Unless stated otherwise, all aspects of this experiment were the same as those in Experiment 1.

Participants

A total of 16 undergraduates (10 female) from the University of Alberta participated for class credit (age range: 17–24 years). All had normal or corrected-to-normal vision based on self-report. A total of 4 participants were left-handed.

Stimuli

Task 1 and Task 2 stimuli and viewing conditions were the same as those in the 12-letter condition of Experiment 1, with the following exceptions. The peripheral probe was as in Experiment 1. The central probe started 0.17° from the centre of the circle and terminated approximately 1.15° from the centre of the target letter. The central probe did not originate from fixation in order to avoid forward masking from the Task 1 digit.

Design

The experiment consisted of a single 90-min session. In one half of the session the probe was peripheral (i.e., near the target); in the other, the probe was central. The order of presentation of the probe conditions was counterbalanced across subjects. Each probe condition consisted of seven blocks of trials, the first two being practice blocks. In Experiment 1, the effect of SOA appeared to peak at 240 ms in each items condition. Consequently, in Experiment 2 the range of task SOAs was restricted to look within the window of interference observed in Experiment 1. Specifically, within each block, the SOA between the two tasks was mixed randomly and was 30, 60, 120, 180, or 240 ms. In each block there were 8 trials in each SOA condition, resulting in 40 trials per block. The design resulted in 80 practice trials and 200 experimental trials per probe condition. Between each block, subjects were given an opportunity to rest.

Results

Using the same exclusion criteria as in Experiment 1, 4 subjects were excluded from the analyses. In addition, 2 participants were excluded due to Task 1 error rates greater than 15%. The remaining 10 subjects were included in all analyses.

Task 2 accuracy. Identification accuracy in Task 2, averaged across subjects, is shown as a function of SOA and probe type in Figure 5. Accuracy improved as the SOA between tasks was increased. At the shortest SOA, accuracy was 33.9%, and at the longest SOA accuracy was

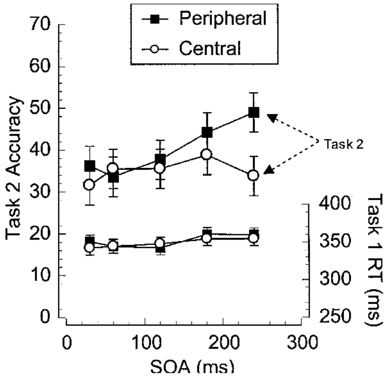

Figure 5. Results of Experiment 2. The upper portion of the figure illustrates the mean percentages of correct identification of the partial-report target, given accurate identification of the Task 1 digit. The lower portion of the figure illustrates the mean response times (RT) for Task 1 for accurate trials only. Error bars represent 95% confidence intervals and are appropriate for within-subjects pairwise comparisons (Loftus & Masson, 1994).

41.3%. Task 2 accuracy also changed as function of probe type. Overall, there was a benefit with peripheral probes (mean = 40.1%) compared with central probes (mean = 35%). As can be seen in Figure 5, there was a clear interaction between SOA and probe type. In the peripheral probe condition, the maximum difference between any two SOA conditions was 15.3% (60 ms vs. 240 ms). In the central probe condition, the difference was about half of that found in the peripheral condition (7.2%, 30 ms vs. 180 ms). Moreover, at short SOAs there was no difference between the probe conditions, whereas at the longest SOA there was a substantial difference of 15%.

Nested models similar to those used in Experiment 1 were fitted to the partial-report results of Experiment 2. First, a model incorporating a monotonic increase in SOA was compared to a null model in which it was assumed that performance was unaffected by condition. This yielded a likelihood ratio of $\lambda = 193.81$; this constitutes fairly clear evidence for an overall effect of SOA. Second, this model was compared to an additive model that also incorporated an effect of type cue. This yielded a likelihood ratio of $\lambda = 5.27$. Thus, there is no clear evidence for a main effect of type of cue over and above the effect of SOA. Finally, an interactive model in which it was assumed that the monotonic effect of SOA varied with cue condition was fitted to the results. Compared to the additive model, this yielded a likelihood ratio of $\lambda = 132.52$. Thus, there is relatively clear evidence that the effect of SOA is different in the central condition than in the peripheral condition.

Task 2 errors. Overall, 59.3% of errors were transposition errors. The percentage of transpositions did not change as a function of SOA. The percentages of transpositions in the 30, 60, 120, 180, and 240-ms SOA conditions were 55.6, 59.2, 62.4, 58.9, and 60.7, respectively. The rate of transpositions was the same in the central and peripheral probe conditions (60.2% vs. 58.6%), and the temporal course of the SOA effect did not change as a function of the number of items in the display.

Task 1 response time. The response time analysis was done the same way as in Experiment 1. Mean RTs for the first task, averaged across subjects, are shown in the lower portion of Figure 5. The trends in the data mirror those of Experiment 1. Overall mean RT was 349.8 ms. There was a small increase in RT as the SOA was increased, where the largest difference in RT was between the 60-ms (344.3 ms) and the 180-ms (357.1 ms) SOA conditions. There was no effect of partial-report probe type, nor any interaction between probe type and SOA.

Task 1 errors. The error rate collapsed across all conditions was 9%. The error rate did not change as a function of probe type: Percentages of errors in the peripheral condition were 7.9% and 10.1% in the central condition. Error rate declined from 11% at the shortest SOA to 7.8% at the longest SOA. This small decline did not interact with probe type.

Overlap analysis. The method used for performing the overlap analysis was the same as that used in Experiment 1. The data, averaged across subjects, are shown in Figure 6 (symbols). Consider the peripheral probe condition (filled squares) first. This condition is the same as the 12-letter condition in Experiment 1, and the overlap analysis shows a similar decline in accuracy as overlap time increases. In the central probe condition (open circles), there was virtually no change in Task 2 accuracy as overlap increased. This leads to the predicted interaction: With long task overlap, performance with the two types of probe is equivalent, and an advantage for peripheral probes is only found at short overlap.

The same model fitted to the results of Experiment 1 was also fitted to the results shown in Figure 6 (lines). The effect of type of probe was assumed to be isolated in the efficiency of selection. For example, given that attentional shifts are slower with a central cue, one would anticipate that less information would be selected prior to the onset of the mask. We modelled this as a decrease in the amount of maskable information by a given proportion (i.e., the parameter s was reduced by a value k). Thus, the proportion correct at a given overlap time, t, with peripheral cues was predicted to be

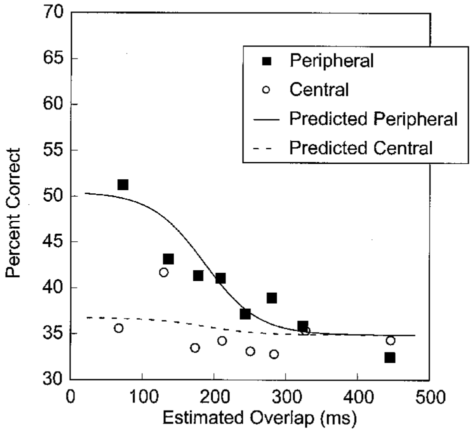

Figure 6. Results of the overlap analysis of Experiment 2. Symbols represent observed data; curves represent the model predictions.

$$P(C) = g + (1 - g)\left\{ jr + \frac{js}{1 + \exp[(t - \mu) / \sigma]} \right\}$$

as before. Because 12-item arrays were used in this experiment, the parameter *j* was used in the equation to reflect the reduced visual information available in the display. In contrast, the proportion correct with central cues was predicted to be

$$P(C) = g + (1 - g)\left\{ jr + \frac{jks}{1 + \exp[(t - \mu)\sigma]} \right\}$$

The interaction observed in Figure 6 obtains in this model because efficiency of selection only matters when response selection in Task 1 finishes prior to the onset of the mask in Task 2, which, of course, is much more likely when there is little task overlap. When the response selection finishes after the presentation of the mask, only the residual information is available, and the efficiency of selection is irrelevant.

With the exception of the additional parameter *k*, the estimated parameter values were constrained to be the same as those in the fit to the results of Experiment 1; the estimate of *k* is shown in Table 1. The predicted proportion correct as function of overlap is shown in Figure 6 as continuous lines. As is clear from the figure, the model provides an accurate description of the interaction of probe type and SOA, showing little difference between central and peripheral with long overlap and much greater difference with short overlap.

Discussion

Several important results emerged from Experiment 2. First, the peripheral probe condition replicated the results of the 12-letter condition of Experiment 1 and provides additional evidence that the dual-task interference found here is real. Second, the overlap analysis replicated the overlap analysis of Experiment 1, showing substantial interference when task overlap was high and less interference with minimal overlap. Finally, and most importantly, probe type interacted with SOA, such that there was no effect of probe condition at short SOAs, whereas the effect of probe condition was substantial at long SOAs.

The nature of the interaction between probe type and SOA suggests that shifting attention in the second task proceeds in parallel with response selection in the first task. This conclusion is analogous to one of the more distinctive implications of the bottleneck models using speeded tasks (e.g., Pashler, 1994). That is, when SOA is short, processing in Task 2 has to wait for the bottleneck stage, and any effects on processing time prior to the bottleneck will have little effect. Similarly, in the present paradigm, when short-term consolidation of the second task is delayed at short SOAs (and long task overlap), it is delayed regardless of the probe type; thus, performance is largely unaffected by the initial efficiency of attentional selection.

It might be argued that the results are compromised by a floor effect at short SOAs. In fact, one interpretation is that because only three of the five response alternatives were items from the display, chance in this task is 33% (rather than 20%). If this were true, then accuracy in the central probe condition would be at the floor. Such an account, however, requires that all the errors be transposition errors. The error data do not support this conclusion: Only 60% of errors were transposition errors. Thus, it is unlikely that the interaction between SOA and probe type was due to floor effects in the central probe condition.

Moreover, the form of the interaction makes it unlikely that floor effects could compromise the interpretation of the results in any event. At short SOAs, performance with central and peripheral probes was similar, and it is plausible to assume that the same kind of information was being used in the two conditions. Presumably, this is the residual information available from the array even after the presentation of the mask (cf., Figure 3). Our interpretation is that the short SOA causes a delay in short-term consolidation, and consequently in neither condition can subjects make much use of the maskable information. The interaction occurs because performance improves with longer SOAs only in the peripheral probe condition. Thus, the results imply that in order for performance to get much above the low level of performance observed with short SOAs under these conditions, both long SOAs and peripheral probes are necessary; neither alone is sufficient. The logic of this conclusion applies even if performance at short SOAs represents some form of accuracy floor. Our interpretation of this result is that peripheral probes are necessary to efficiently select information from the probed position, and that long SOAs are necessary to allow short-term consolidation to operate prior to the presentation of the mask.

EXPERIMENT 3

In Experiments 1 and 2, both tasks were visual: Task 1 was a simple visual discrimination task, and Task 2 was a visual partial-report task. One might argue that the reason we observed interference and Pashler (1991) did not was that there were within-modality perceptual limits (Pashler, 1989). More specifically, the present results may reflect modality-specific interference that has nothing to do with attentional and encoding constraints in information processing, but has more to do with the perceptual limitations of the visual system. This explanation, however, cannot account for the interference observed by Jolicoeur and Dell'Acqua (1998), as they coupled a tone task with a visual memory task. Nevertheless, we conducted Experiment 3 to rule out modality-specific interference as an alternative explanation.

In Experiment 3, the first task was a speeded tone discrimination rather than a visual discrimination. The second task was exactly the same as the 8-letter condition of Experiment 1. If the interference effects observed in the previous two experiments were due to perceptual limitations confined to the visual system, then no interference should be observed. However, if the interference observed in the first two experiments reflect the need for a more general processing mechanism, then interference effects should be observed and these effects should be similar in magnitude to those found in Experiment 1.

Method

Participants

A total of 17 undergraduates (13 female) from the University of Alberta participated for class credit (age range: 18–20 years). All had normal or corrected-to-normal vision based on self-report, and all reported normal hearing. A total of 4 participants were left-handed.

Stimuli

The auditory stimuli for Task 1 were pure tones generated by a Macintosh II computer. The frequency of the high tone was 988 Hz (MIDI value = 83), and the frequency of the low tone was 246 Hz (MIDI value = 59). Task 2 stimuli and viewing conditions were the same as those in the 8-letter condition of Experiment 1.

Procedure

The trial sequence was the same as that for Experiments 1 and 2 except for the following. Once the trial was initiated there was a 495-ms delay, and then a 30-ms tone was played over headphones worn by the subject. During this time and until the partial-report display was presented, the fixation dot remained on the screen. Subjects were instructed to indicate the pitch of the tone by pressing either the button marked "LOW" with their left thumb or the button marked "HIGH" with their right thumb. The remainder of the trial was as in the previous experiments.

Design

The experiment consisted of a single one-hour session. There were eight blocks of trials, the first two being practice blocks. To provide a more complete picture of the pattern of interference caused by an auditory Task 1, the range of task SOAs was expanded to those used in Experiment 1: 60, 120, 240, and 480 ms. In each block, there were 6 trials at each of the SOAs, resulting in 24 trials per block. The order of trials was selected randomly. Between each block, subjects were given an opportunity to rest. The design resulted in 48 practice trials and 144 experimental trial per participant.

Results

Using the same exclusion criteria as those in Experiment 2, 5 participants were excluded from the analyses. The remaining 12 participants were included in all analyses.

Task 2 accuracy. Task 2 identification accuracy averaged across subjects is shown as a function of SOA in Figure 7. Accuracy improved as the SOA between tasks was increased. At

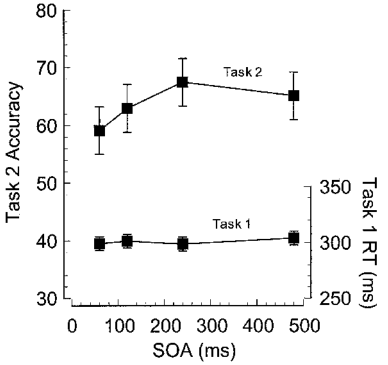

Figure 7. Results of Experiment 3. The upper portion of the figure illustrates the mean percentages of correct identification of the partial-report target, given accurate identification of the Task 1 digit. The lower portion of the figure illustrates the mean response times (RT) for Task 1 for accurate trials only. Error bars represent 95% confidence intervals and are appropriate for within-subjects pairwise comparisons (Loftus & Masson, 1994).

the shortest SOA, accuracy was 59.1%; this level of performance improved monotonically between SOAs of 60 and 240 ms, peaking at 67.5% in the 240-ms SOA condition and falling slightly to 65.1% in the 480-ms condition.

The partial-report results were analysed by comparing a model incorporating a monotonic effect of SOA to a null model in which it was assumed that SOA had no effect. This yielded a likelihood ration of $\lambda = 48.96$. In other words, the results were almost 50 times as likely when one included the assumption that partial-report performance varied with SOA.

Task 2 errors. Overall, the rate of transposition errors was 59.4%, similar to that of the previous experiments. The percentage of transpositions did not change systematically as a function of SOA. The percentages of transpositions in the 60, 120, 240, and 480-ms SOA conditions were 64.3, 56.1, 57.2, and 59.9, respectively.

Task 1 response time. The response time analysis was done the same way as in Experiments 1 and 2. Mean response times for the first task, averaged across subjects, are shown in Figure 7. Overall mean latency was 300 ms. As can be seen in the lower part of Figure 7, there was no change in response time as a function of the interval between the two tasks. Indeed, the largest difference in response time was between the 240-ms and the 480-ms SOA conditions, where on average the tone task took 299 ms and 304 ms, respectively. In the 60-ms and 120-ms conditions, mean Task 1 response times were 299 ms and 301 ms, respectively.

Task 1 errors. The error rate collapsed across all conditions was 7.5%. There was a very small decline in error rate as the SOA was increased. In the 60-ms SOA condition the error rate was 8.1%, and in the 480-ms condition it was 6.3%. The error rates in the 120-ms and 240-ms conditions were 7.6% and 7.9%, respectively.

Overlap analysis. The method used for computing overlap analysis was the same as that used in Experiments 1 and 2. The average collapsed across subjects is shown in Figure 8

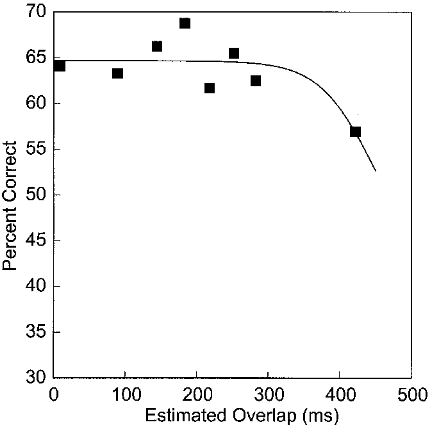

Figure 8. Results of the overlap analysis of Experiment 3. Symbols represent observed data; the curve represents the model predications.

(symbols). The pattern is of the same character is that observed in Experiment 1: As overlap time increased performance declined. However, unlike the previous experiments, the interference seemed to occur primarily with the longest overlap, and partial-report performance seemed largely unaffected with overlaps as long as 200 ms.

The solid line in Figure 8 shows the predictions made by the same model fitted to the results of Experiments 1 and 2. The parameter values used generally were constrained to be same as the 8-item condition in Experiment 1; the only difference was that a new value of μ was estimated. The new estimate for μ is substantially longer than that obtained in Experiment 1, reflecting the fact that most of the drop in accuracy occurred at the longest overlap. The estimated value of μ (446 ms) may seem unreasonably large given that response times in Task 1 were in the order of 300 ms. Indeed, if μ were interpreted purely as the time between the selection of the Task 1 response and the completion of that response, the estimate would have to be constrained to be much smaller, and any values larger than about 100 ms or so would be suspicious. However, the estimated value of μ is affected by the duration of many processing components in the experimental situation, not just the duration of Task 1 response execution. In particular, μ also reflects the time needed to process the information in the partial-report array and make it available for subsequent short-term memory consolidation, and it is also affected by any task-switching delay after Task 1 response selection has been completed (e.g., Rogers & Monsell, 1995). Thus, one possible explanation of the apparent difference in the interference pattern obtained in Experiment 3 is that the bottleneck mechanism is used differently. For example, it may be more difficult to switch from selecting a response for a visual task to encoding other visual information (as in Experiments 1 and 2) than it is to switch from selecting a response in an auditory discrimination task to an unrelated visual task (as in Experiment 3). Greater difficulty in reallocating the bottleneck would lead to a longer delay before the bottleneck would be available for consolidating information from the partial-report task and, consequently, to greater interference at moderate task overlaps. Alternatively, the failure of any of the simplifying assumptions made in fitting the model can easily distort the estimate of μ. For example, quite different estimates of μ would be obtained if σ were also allowed to vary across experiments or if the loss of maskable information were assumed to be gradual rather than abrupt. For these reasons, we are reluctant to place any strong processing interpretation on the estimated parameter values. Although the difference between results obtained with a visual discrimination in Task 1 and those obtained with an auditory discrimination certainly warrants further investigation, we do not believe at this point that the large estimate of μ found in Experiment 3 necessarily reflects a flaw in our conceptual framework.

Discussion

The results of Experiment 3 can be summarized simply: When tone discrimination was combined with partial report in a dual-task paradigm, performance on the partial-report task was lowest when the SOA between the tasks was brief and improved as the SOA increased. In other words, dual-task interference was observed. Moreover, the magnitude of the estimated interference shown in Figure 8 is the same as that used in the 8-letter condition of Experiment 1 using a visual discrimination as Task 1; only the time-course of the interference is different, with greater task overlap needed to produce the same level of interference with a tone discrimination task. Thus, the results are consistent with the view that the interference is due to general processing limitations and is not solely due to modality-specific perceptual limitations (e.g., Jolicoeur, 1999b; Pashler, 1989).

Of course, the possibility that perceptual interactions between the stimuli in a visual discrimination task and those in partial report could lead to interference under some circumstances cannot be ruled out. Indeed, the size of the raw interference effect was smaller when Task 1 was auditory (see Figure 7); such a decrease would be consistent with within-modality limitations operating in this situation. Moreover, the partial-report task is inherently a perceptually demanding task, and performance often suffers due to variables such as contrast, eccentricity, and lateral masking (e.g., Giesbrecht & Dixon, 1999). Nevertheless, the fact that the same estimate of interference can be used across experiments (in Figures 4 and 8) suggests that the interference observed is not confined to the visual modality; thus, a more general information-processing mechanism is implicated. In particular, the results support our hypothesis that short-term consolidation of the information from the partial-report task involves the same central mechanism required for response selection in speeded choice tasks.

GENERAL DISCUSSION

The goal of the present work was to examine the relationship between attention and memory in human information processing. Specifically, we focused on how shifting spatial attention and encoding and storage in short-term memory relate to general-purpose processing limitations. We examined the effects of variables on performance in the partial-report task embedded in a dual-task paradigm. Following from common interpretations of the partial-report task, we assumed that this task required shifting attention in the visual field, selecting relevant information, and then encoding and storing this information in short-term memory for later report. We manipulated variables that were anticipated to affect the encoding and storage processes (Experiment 1) or the process of shifting attention and selecting visual information (Experiment 2) and examined the patterns of dual-task interference. We hypothesized that factors that affect processes that are independent of the bottleneck stage should show roughly additive effects with task SOA, whereas factors that affect the efficiency of selection for use in the bottleneck stage should interact with task SOA, showing their effects only at long SOAs.

The critical manipulation in Experiment 1 was the number of items in the partial-report display; 8 letters vs. 12 letters. We found large interference effects in both conditions, but the manipulation was effective at all SOAs. According to our analysis of the dual-task paradigm, this additivity suggests that the items manipulation affected information that was independent of the processing in the partial report task that generated the dual-task interference. We hypothesized that the number of array items affects the quality of information to be consolidated. This interpretation predicts that performance should decline as a function of the overlap between the two tasks, similar to that of the effect of delaying the probe in partial report (Sperling, 1960). We provided a direct test of this prediction with a new analysis based on a calculation of the overlap between the two tasks that combines both response time on the first task and SOA. Task 2 accuracy declined as a function of task overlap, whereas a number of items affected both peak performance with brief overlap as well as asymptotic performance at long overlap. These results support the conclusion that the memory-encoding component of partial report requires bandwidth-limited processing that is also required for response selection of the first task (Jolicoeur & Dell'Acqua, 1998).

In Experiment 2, the critical manipulation was the type of partial report probe, central or peripheral. Central probes are thought to invoke a shift of attention that is slow and effortful compared to the fast and automatic shifts induced by peripheral probes (e.g., Dixon et al., 1997; Jonides, 1981; Müller & Rabbitt, 1989). As in Experiment 1, we found interference effects in both conditions. However, unlike in Experiment 1, probe type interacted with SOA, such that there was no difference between the probe conditions at short SOAs, whereas at long SOAs performance in the peripheral probe condition was approximately 15% better than performance in the central condition. Our interpretation of this interaction is that at short SOAs, the information selected in response to both peripheral and central probes is of the same degraded quality (i.e., residual information in Figure 3). Thus, regardless of probe type, the information that is encoded is of low fidelity, and accuracy will be low. At long SOAs, however, the information selected in response to the peripheral probe is less vulnerable to masking (e.g., Giesbrecht & Di Lollo, 1998); consequently, the information is of higher quality than the information selected in response to central probes.

The results of the present experiments stand in marked contrast to those of Pashler (1991). Namely, we obtained substantial dual-task interference (e.g., as large as 15% in Experiment 2) whereas Pashler found minimal effects, less than 2%, using a similar paradigm. In particular, Experiment 5 of Pashler's study involved a very similar partial-report paradigm with a probe-type manipulation that was virtually the same as that used here, but only minimal interference was observed. Why, then, did Pashler not observe dual-task interference in his paradigm? There are several possibilities for the discrepant patterns of results, many of them procedural. One plausible reason that Pashler did not observe interference similar to that observed in the present experiments may have been that all of his experiments used an auditory discrimination as Task 1. For example, it could be the case that the interference we observed reflected perceptual limitations within the visual modality and not that of a more general information-processing bottleneck (Jolicoeur, 1999a, b; Pashler, 1989). Consequently, Experiment 3 was run as a validation of our general paradigm. In Experiment 3, we changed the first task from a simple visual discrimination to a simple tone discrimination. Yet again, dual-task interference was observed; however, the interference observed in Experiment 3 was smaller than that of Experiments 1 and 2. This suggests that some, but perhaps not all, of the interference observed in the present work was due to processing limitations that are not modality specific.

There are other procedural differences that might also be related to the discrepancy between Pashler's results and ours. For example, the probe and the array overlapped in time in Pashler's partial-report task, whereas they were temporally disjoint in our implementation; Pashler adjusted the array-mask SOA individually across blocks whereas we used a constant (and somewhat shorter) SOA; and the overall level of partial-report accuracy was higher in Pashler's results than in ours. However, in addition to the differing modalities of the first task we suspect that another critical factor may have been the nature of the stimulus set used in the partial report task: Our items were sampled from the entire alphabet whereas Pashler's were limited to A, B, C, and D. This may have made the selected information in Pashler's task much less susceptible to subsequent masking. In particular, one of the effects of a pattern mask may be to destroy information about fine spatial alignment that allows features to be successfully conjoined, and the residual information that remains following the mask may consist primarily of a few isolated features or line segments (cf., Prinzmetal, 1992). When there are many possible stimulus items, a few isolated features are unlikely to provide much constraint on the nature of the target item. However, when there are only four visually distinct items, accuracy based on isolated features could be much higher. In sum, we hypothesize that substantial interference was observed in Experiment 1 because accurate report generally required the integration of visual features and that this was only possible when short-term consolidation occurred prior to the mask; interference was minimal in Pashler's experiments because feature integration during consolidation was much less critical.

To this point we have argued that the observed interference was due to a failure of encoding information into durable storage. The results have been explained largely in terms of Jolicoeur and Dell'Acqua's short-term consolidation account of dual-task interference observed in psychological refractory period paradigms using unspeeded memory tasks as second tasks (e.g., Jolicoeur & Dell'Acqua, 1998, 1999). Although the short-term consolidation account provides a directly applicable and parsimonious account of our data, there are other related accounts of dual-task phenomena that could have been adapted to fit the data (e.g., Chun & Potter, 1995; Shapiro, Raymond, & Arnell, 1994; Vogel, Luck, & Shapiro, 1998). However, our experiments were not designed to discriminate between different models of dual-task interference, but rather to explore the relationship between attention and memory. Thus, the different models are not discussed. Rather we stay true to our aim and discuss the relationship between attention and memory, how the present results bear on that relationship, and the relation of the present work to other work that explores similar issues.

On the relationship between attention and memory

The present experiments suggest a specific working relationship between attentional shifts and memory encoding within the partial-report task. At the broadest level, it appears that shifts of selective spatial attention can be executed in parallel with response selection, whereas the same cannot be said about memory encoding. This difference suggests that the two processes do not compete for the same mechanisms or at least do not place the same requirements on the system. More specifically, within the context of the present paradigm it would appear that the attentional shift occurs prior to encoding into short-term memory. It is important to note, however, that this sequence of operations may reflect the nature of the paradigm—namely, because of the apparent bottleneck delaying memory encoding, attentional shifts appear to occur before memory encoding (at least at short SOAs). However, when the partial-report task is done in isolation, the temporal order of the array and probe dictates the sequence of operations. For example, if the probe is presented before the partial-report display, the attentional shift would occur before presentation of the display. If, on the other hand, the probe is presented after the display, a different order of events would occur. During the probe delay, items would be non-selectively encoded into durable storage, thus encoding would actually occur prior to the attentional shift. But note that when the probe is presented, attention is shifted to that location, and the representation of the item in that location is encoded into durable storage for report (e.g., Averbach & Coriell, 1961).

This description of the relationship between cued shifts of attention and memory encoding implies that the function of attentional shifts, in some sense, is to support memory encoding. The most likely way that attentional shifts would support memory encoding is by enhancing processing efficiency. A large body of evidence from a wide variety of studies, including behavioural studies (e.g., Posner, 1980; Prinzmetal, Presti, & Posner, 1986), neurophysiological studies (Moran & Desimone, 1985), and neuroimaging studies (e.g., Hillyard, Vogel, & Luck, 1998; Mangun & Hillyard, 1991), demonstrate that shifting attention to a location facilitates processing of information at that location. What role would this enhancement have in supporting memory? Consider again the partial report task. When a display is presented very briefly, the information is probably represented by different sources of information (Giesbrecht & Dixon, 1999). We have argued that there are three major sources of information that contribute to partial-report performance: Visual features, abstract identities, and durable storage (Giesbrecht & Dixon, 1999; but also see Irwin & Yeomans, 1986; Mewhort et al., 1981). The stability of these representations is different, with visual feature information being the most labile and durable storage information being the most stable. It is probably the case that only the most stable representation of the information in the processing system serves as the basis for report. In other words, if there was no information in durable storage, but some information at the level of abstract identities, then the most stable information would be encoded into memory for report. Within this context, perhaps the role of shifting attention to the probed location is to facilitate stabilization of the representation prior to encoding into durable storage, by binding features or feature bundles at the probed location (e.g., Dixon & Di Lollo, 1991) and then directing encoding of that information into durable storage.

The notion that attentional shifts improve the efficiency of memory is not isolated to the present work. Recent work has looked at the relationship between shifts of spatial selective attention and spatial working memory (e.g., Awh & Jonides, 1998; Awh, Jonides, & Reuter-Lorenz, 1998). Spatial working memory is a subset of working memory that is specialized for remembering spatial locations as distinct from objects and object identities (Smith et al., 1995). Fundamental to the work of Awh and his colleagues (e.g., Awh & Jonides, 1998; Awh et al., 1998) is the notion that spatial selective attention enhances processing at a specific location in space, as outlined earlier. On that tenet, they argue that the relationship between spatial selective attention and spatial working memory is such that as a consequence of the enhanced sensory processing at attended locations, spatial selective attention mediates the rehearsal of information in spatial working memory. This hypothesis is similar in character to the relationship between shifts and very-short-term memory suggested here. It is our hope that with future research this similarity will go beyond the superficial and may prove to be one of the principal functional relationships between attention and memory.

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APPENDIX

The results of traditional hypothesis tests—that is, repeated measures analysis of variance (ANOVA), for Experiments 1–3 are reported here. For each experiment four ANOVAs were conducted, each with a different dependent measure: namely, Task 2 accuracy, Task 2 errors, Task 1 response time, Task 1 errors. For all experiments, Task 2 accuracy was conditionalized on accurate Task 1 responses, Task 2 errors were the percentage of errors that were transposition errors, Task 1 response times were calculated using the median latency of correct trials in each cell for each subject, and Task 1 errors were calculated as a percentage of all trials.

Experiment 1

The analysis of Experiment 1 consisted of ANOVAs with two within-subjects variables: the number of items in the partial-report display (8 and 12) and Task 1–Task 2 SOA (60, 120, 240, and 480 ms).

Task 2 accuracy. The ANOVA of Task 2 accuracy revealed significant effects of items, $F(1, 9) = 27.45$, $p < .001$; and of SOA, $F(3, 27) = 6.21$, $p < .005$. The interaction between items and SOA was not significant ($F < 1$).

Task 2 errors. There were no statistically reliable effects in the Task 2 error analysis: items, $F < 1$; SOA, $F(3, 27) = 2.46$, $p > .08$; and the Items × SOA interaction, $F(3, 27) = 1.48$, $p > .24$.

Task 1 response time. There was a reliable effect of SOA, $F(3, 27) = 4.47$, $p < .02$. However, the main effect of items and the interaction between items and SOA were not significant, $F < 1$ and $F(3, 27) = 1.03$, $p > .4$, respectively.

Task 1 errors. The repeated measures ANOVA on Task 1 errors revealed a significant interaction between items and SOA, $F(3, 27) = 3.86$, $p < .03$. The main effect of items and SOA were not significant (both *F*s < 1).

Experiment 2

As with Experiment 1, the analyses of Experiment 2 consisted of ANOVAs with two within-subjects variables: probe type (peripheral and central) and SOA (30, 60, 120, 180, and 240 ms).

Task 2 accuracy. This analysis revealed a marginal effect of probe type, $F(1, 9) = 3.55$, $p < .10$; and a reliable main effect of SOA, $F(4, 36) = 2.71$, $p < .05$. The interaction between probe type and SOA was also statistically significant, $F(4, 36) = 3.35$, $p < .02$.

Task 2 errors. None of the effects was statistically reliable: main effect of probe type, $F < 1$; SOA, $F(4, 36) = 1.24$, $p > .31$; and the Probe Type × SOA interaction, $F(4, 36) = 1.46$, $p > .23$.

Task 1 response time. The only statistically reliable effect was that of SOA, $F(4, 36) = 3.18$, $p < .03$. All other *F*s were less than 1.

Task 1 errors. Task 1 error analysis revealed a significant effect of SOA $F(4, 36) = 2.87$, $p < .04$. The main effect of probe type and the interaction between probe type and SOA were not statistically reliable: probe type, $F(1, 9) = 2.02$, $p > .18$; probe type × SOA, $F(4, 36) = 2.39$, $p > .06$.

Experiment 3

The analysis of Experiment 3 consisted of a single-factor ANOVA. The only independent variable in the design was SOA (60, 120, 240, and 480 ms).

Task 2 accuracy. The analysis of Task 2 accuracy revealed a significant effect of SOA, $F(3, 33) = 2.92$, $p < .05$.

Task 2 errors. Unlike the results of the Task 2 accuracy analysis, the effect of SOA in terms of transposition errors was not significant ($F < 1$).

Task 1 response time. Response times did not change as a function of SOA ($F < 1$).

Task 1 errors. As with the results of the response time analysis, Task 1 error rate did not change as a function of SOA ($F < 1$).