Shifting Visual Attention and Selecting Motor Responses: Distinct Attentional Mechanisms

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Does shifting visual attention require the same central mechanism as that required for selecting overt motor responses? In Experiment 1, Ss performed 2 tasks: a speeded manual response to a tone and an unspeeded report of a cued target letter in a brief masked array. Stimulus onset asynchrony (SOA) between tone and array was varied. If the attention shift to the target was delayed by the first task, then there should be more second-task errors at short SOAs and on trials with slow first-task responses. In fact, SOA effects and dependencies were minimal. Results were unchanged in further experiments in which the relation between cue and target was symbolic, spatially "unnatural," or based on the color of the target. Two additional experiments validated key assumptions of the method. The results confirm that although selection of motor responses constitutes a processing bottleneck, the control of visual attention operates independently of this bottleneck.

The term *attention* has been used to cover a notoriously broad range of phenomena in the psychological literature, seemingly mirroring the broad use of this word in ordinary English. One phenomenon very commonly referred to with the term is selective control over the processing of information from different parts of the visual field (henceforth, *visual selective attention)*. Obviously, there are analogous uses for the term with regard to other sensory modalities. In addition, though, the term attention is often used in connection with the limitations that arise when two concurrent tasks each require a subject to select and carry out actions (henceforth, *dual-task attentional limits)*. Both of these topics have been investigated extensively with laboratory tasks. Fundamental questions concerning the relationship between the two phenomena, however, have received little empirical or theoretical consideration. For the most part, articles pertaining to one of these topics simply do not address the other. In some textbooks and reviews, though, selective attention and dual-task attentional limits are assimilated together, usually with the suggestion that certain theoretical concepts like "capacity" or "automaticity" can somehow unify them. These supposed unifications are usually described only in extremely vague terms, however, without any description of how they might be empirically tested.

The present work explores the relationship between visual selective attention and dual-task attention limits empirically and then proposes an account of how the two classes of phenomena are related. This account provides an extension of the two-component theory of divided attention developed in previous articles (e.g., Pashler, 1989). The starting point for this analysis is a body of evidence which indicates that one fundamental cause of dual-task interference with simple tasks is queuing in the selection of actions. This view was first advocated by Welford (1952), but only somewhat indirect empirical support was available at the time. The next section summarizes the currently available evidence. Then, an empirical approach is sketched that asks whether the mechanism responsible for queuing of the selection of actions is also necessary for controlling shifts of visual attention. In essence, the question is whether these two core attentional phenomena reflect the operation of a common mechanism. In the studies reported in the following, subjects' performance is examined in experiments involving two tasks: a speeded choice response to an auditory stimulus and report of a cued element from a multielement array; the array is presented at a brief variable interval after the auditory stimulus. The goal of these experiments is to determine whether and how the execution of processing stages in the first task affects the shift of visual attention in the second task. The present work uses strategies for examining dual-task interference that were developed previously (Pashler, 1984b, 1989; Pashler & Johnston, 1989).

Response-Selection Queuing and Divided Attention

Before examining the relationship between selection of actions and the control of visual attention, I first examine the evidence for a fundamental attentional mechanism that selects motor responses one task at a time. This evidence comes from dual-task experiments. Here, one observes what happens when people try to perform two activities at once, each involving a separate response that is based on a distinct

stimulus. Many such studies have involved complex tasks extended in time (e.g., shadowing, reading, or tracking) and use performance measures that aggregate over trials. This rather coarse approach has neither led to testable hypotheses about the time course of dual-task interference nor characterized underlying mechanisms. The background for the present investigation lies in an alternate approach, which focuses on simpler, more tractable tasks by using multiple indexes of performance on each individual trial. This work yields the conclusion that when response selection in one task occurs, response selection in the other task must be postponed. The clearest evidence for this comes from the simplest dual-task paradigm, commonly referred to as the *psychological refractory period* (PRP) paradigm. In the PRP paradigm, the subject is presented with two stimuli (SI and S2) in rapid succession that are separated by a given stimulus onset asynchrony (SOA); the subject must make a response to each (Rl and R2, respectively) as rapidly as possible. Some basic phenomena arising in this paradigm were investigated in the 1950s and 1960s, and a number of accounts were proposed (for reviews, see Bertelson, 1966; Smith, 1967). The most basic observation is a slowing of the second response, a slowing that increases as the SOA between the two stimuli is reduced; this is usually called the *PRP effect*. With even very simple tasks (say, 2 two-alternative choice tasks with simple stimuli and manual responses), the PRP effect is generally very sizable, slowing the second response by at least several hundred milliseconds.

In the early investigations directed at understanding the causes of the PRP effect, a variety of proposals were considered, including *postponement models* and *capacity-sharing models.* Postponement models claim that interference occurs between two tasks because specific cognitive operations can only occur when a single mechanism is exclusively dedicated to performing that operation. When the critical mechanism is occupied with one task, processing operations in the other task that require this mechanism must be postponed until it becomes available; hence the concept of a processing "bottle-neck" or "single channel." Postponement models were pro-

posed that would have located the source of postponement in different stage(s) of processing such as perceptual identification, response selection (Smith, 1967; Welford, 1980) or response initiation and execution (Keele, 1973; Logan & Bur-kell, 1986; Norman & Shallice, 1985). Several authors (e.g., Kahneman, 1973; Norman & Bobrow, 1975; Wickens, 1983) proposed an alternative—capacity-sharing models—according to which interference between tasks originates not in queuing of particular stages or operations but rather in a reduction of the efficiency with which each task simultaneously operates, induced by a graded sharing of resources between the tasks. The simplest version of this type of theory supposes that only a single very general resource is allocated to all cognitive processes (Kahneman, 1973; McLeod, 1977), although models that postulate multiple pools of resources have also been proposed.

The early work on the PRP paradigm provided interesting and practically useful observations about dual-task interference; however, the early studies did not succeed in definitively rejecting any of the various types of models just described. Another method for testing queuing models and empirically distinguishing them from capacity-sharing models was used by Pashler (1984b) and Pashler and Johnston (1989). In these experiments, we manipulated stimulus factors that affect the duration of selected stages of processing such as perceptual processing, response selection, and response execution (Stern-berg, 1969; for recent discussions of processing stages, see Meyer, Yantis, Osman, & Smith, 1984; Miller, 1988). How can manipulations that affect the duration of particular stages distinguish between the different models? Figure 1 illustrates the hypothesis that dual-task slowing originates in response-selection queuing. The response-selection stage of the second task does not begin until the corresponding stage of the first task is complete, whereas the perceptual processing in the second task begins as soon as the stimulus (S2) is presented.

The method used by Pashler (1984b) for testing a post-ponement model like this one involves manipulating experimental S2 variables that selectively slow either perceptual or response-selection stages of the second task. Consider first a
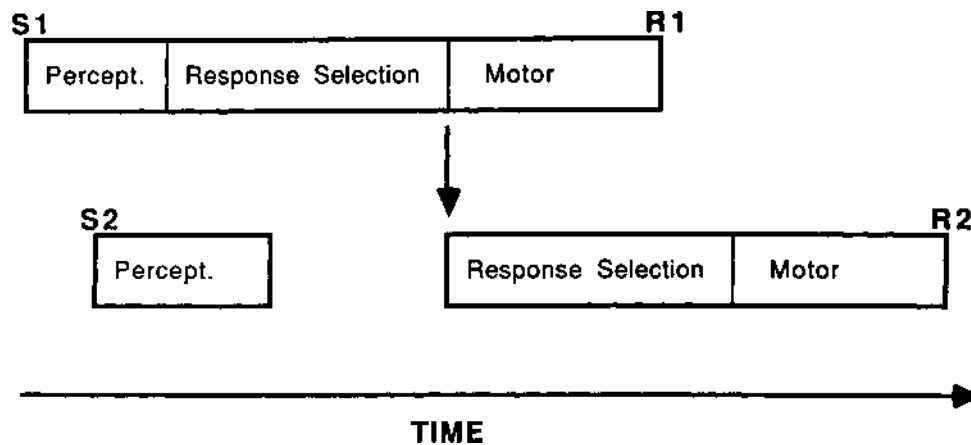

Figure 1. The sequence of stages in response-selection postponement. (Response selection on the second task waits for the completion of response selection on the first task, whereas the other stages can overlap.)

factor that slows response selection in the second task and compare its effect on reaction time in the second task (RT2) in (a) the dual-task condition shown in Figure 1 and (b) a single-task control (not shown) in which the second task is performed in isolation. Clearly, such a factor will slow RT2 by the same amount in both the dual-task and single-task conditions. Stated generally, if a factor slows down stages of processing located at or beyond the stage subject to queuing, then its effects will be additive with the dual-task versus single-task difference (and also additive with SOA). On the other hand, suppose that a factor slowing down perceptual processing of S2 is manipulated. In a single-task control, the entire factor effect will appear as an increase in the second-task RT. In the dual-task condition shown, however, response selection on the second task is unable to begin until its input is available *and* response selection is complete on the first task. The result will be that in the dual-task condition, the factor effect will be partially or completely "washed out": In trials in which response selection is waiting on the processor and not the input, lengthening the perceptual processing time for SI will have no effect. As SOA is reduced, the probability of this will approach unity. Again stated generally, if a factor slows down stages of processing prior to the locus of the queuing, it will have effects that are underadditive with the dual-task versus single-task slowing and underadditive with SOA in the dual-task condition. (Schweickert, 1978, presented several techniques from operations research that are useful in formally analyzing cases such as this.)

In various sets of studies that use this methodology with pairs of choice RT tasks with manual responses, the results have strongly favored response-selection queuing models (Pashler, 1984b; Pashler & Johnston, 1989). In several experiments, the effects of a perceptual factor (e.g., the intensity of a visual S2) were found to be greatly reduced in a dual-task condition and reduced more as the SOA was shortened. This is simply the pattern of underadditivies predicted by the account illustrated in Figure 1. On the other hand, factors targeted to affect the duration of second-task response selection have shown effects that were additive with SOA and dual-task slowing. These results support the conception of response-selection queuing diagrammed in Figure 1, in essential agreement with Welford (and they are inconsistent with competing queuing models and with capacity-sharing models as well).

More recent work, which used methods that are also used in the experiments of this article, tested further predictions from the hypothesis shown in Figure 1. According to the hypothesis, perceptual processing on the second task is not subject to interference from activity on the first task. Pashler (1989) noted that if perceptual processing is not delayed, then when the second task requires a difficult perceptual discrimination involving a brief masked display, the probability of completing the perceptual processing before it is terminated by the mask should not depend on whether the two tasks overlap (short SOA) or not (long SOA). Experiments that used various search second tasks confirmed that any SOA effects on R2 accuracy were indeed very small in magnitude. In addition, if perceptual processing is not waiting for anything in the first task, then the accuracy of the second-task

response ought to be uncorrelated with the relative speed of *R1. This was confirmed as well. Pashler (1989) also tried the very same pairs of tasks as those just described but removed the masks and required speeded responses on both tasks. As expected, the usual PRP interference with the second task was observed, and in addition, detailed predictions of the response-selection postponement account with regard to the relationship between R2 speed and relative Rl speed were also confirmed.

In summary, there is now a substantial set of evidence which indicates that when two simple sensorimotor tasks are performed concurrently, the response selection on the first task holds up the response selection on the second task, whereas perceptual processing in the second task does not wait for any aspect of the first task. (Note that Pashler, 1989, also reported evidence that second-task perceptual processing is sometimes subject to a different sort of interference when both tasks involve difficult visual discriminations, but this second limitation is not relevant for present purposes.)

The term *response selection* in Figure 1 is a rather austere term derived from the study of processing stages in choice reaction time tasks (Sternberg, 1969). In that context, it is reasonably clear what functions are being referred to, but for a general understanding of limitations on simultaneous human information-processing operations outside of these narrow confines, one needs a much richer characterization of which mental functions are subject to the processing bottleneck. Recent results from my laboratory suggest that the term response selection is both overinclusive and underinclusive in its implications. On the one hand, we have found that certain kinds of saccadic eye movements appear to operate free from this bottleneck (Pashler, Carrier, & Hoffman, 1990), and thus not all response selections are subject to it. On the other hand, the limitation turns out not to be restricted to the selection and generation of overt motor actions. For example, Carrier and Pashler (1991) reported several lines of converging evidence which indicate that at least some episodic and semantic memory retrievals in one task (with words as retrieval cues) are delayed by response selection on separate and wholly dissimilar choice RT tasks.

In view of these various findings (summarized by Pashler, in press), it is already apparent that the fundamental bottleneck in action selection revealed in dual-task experiments seems to apply to selection of actions in a very broad sense, including a variety of purely internal operations that might loosely be termed *cognitive actions*. The evidence discussed so far, though, has little to say about the relationship of this bottleneck to the other aspect of the concept of attention that this article addresses. This is the flexible control over the selective uptake of sensory information from different parts of the visual field. I now turn to this issue.

Dual-Task Interference and Visual Attention

The evidence summarized thus far suggests that a fundamental cause of interference when two sensorimotor tasks are carried out concurrently is the inability to select distinct motor responses simultaneously, and as noted earlier, some purely internal responses appear to be subject to the same limitation.

I now turn to a different kind of response, one that is internal and tied to a specific sensory modality: namely, shifts in visual selective attention. In the experiments reviewed above, subjects have not been required to exercise control over which stimuli are processed during the course of a trial. For example, in the experiments that used unspeeded discriminations in masked displays, the entire visual display was relevant, and thus attention shifts were not required.[1] In many ways, attention shifts behave like responses. For example, they can be voluntarily (or involuntarily) triggered by various sorts of stimuli (e.g., von Wright, 1968). Furthermore, the latency for their execution can be measured and appears to be roughly similar to that for the simplest motor responses (e.g., Colegate, Hoffman, & Eriksen, 1973; Sperling & Reeves, 1980).

Given the findings reviewed above, the obvious and straightforward question is simply this: Are attentional shift responses selected by the same system as that which selects motor responses, and thus are they subject to postponement when a motor response must be selected in another task? Several hypotheses deserve consideration. One possibility is that shifting visual selective attention requires the same attentional mechanism as that which carries out response selection. Posner, Sandson, Dhawan, and Shulman (1989) argued for basically this view, although they used a somewhat different terminology. Posner et al. proposed that what they term the *anterior attention system,* particularly heavily involved in linguistic functions, is also involved in controlling shifts of visual attention. Their proposal is based on experiments that combined attentional cuing with a secondary task (shadowing); they are considered in detail in the General Discussion section.

Some neuropsychological evidence has also been used to argue for a direct association between visual selective attention and general response-selection mechanisms. In particular, studies of patients with unilateral neglect due to parietal lobe damage sometimes show a close correspondence between deficits in attentional orienting and deficits in carrying out exploratory movements in space. Thus, Rizzolatti and Camarda (1987) proposed a model of spatial attention that is based on multiple circuits "formed by centers which program motor plans in a spatial framework" (p. 289). This model suggests that selection of motor responses to positions in space and shifts in visual attention are closely tied, and thus it seems to predict that motor-response selection and attention shifts would either be queued or would produce strong spatially based interactions. This work is also considered critically in the General Discussion section.

The obvious alternative to these accounts, which postulate a unified basis for attention shifts and response selection, is that shifts in visual attention may operate completely separately from motor-response selection. To my knowledge, this view has not been explicitly proposed in the literature, although certain neurophysiological evidence (e.g., Goldberg & Segraves, 1987) appears to be favorable to it; this work is discussed below.

Finally, there are some interesting intermediate possibilities. One such account that has intuitive appeal suggests that shifts in visual attention can operate independently of the central attentional mechanism responsible for response-selec-

tion postponement but only when the attention shifts are automatic. Jonides (1981) argued that when attention is summoned to a location by a transient visual stimulus, this shift does not depend on central resources. His conclusion was based on examination of the effects of holding a memory load on attention shifting. Thus, attention shifts may depend on the same central mechanism as response selection only in case the cues capable of inducing automatic attention shifts are not available.

Basic Empirical Strategy

The empirical examination of the relationship between response-selection queuing and shifts in visual selective attention involves experiments that use the various methods for analyzing dual tasks that were described above. The first experiments use the logic of dissociations and dependencies of Pashler (1989). The first task presents a tone stimulus and requires a speeded manual-choice response. The second stimulus is a display of eight elements with a probe next to one of the items; subjects are required to shift attention to the probed item. This item is reported with an unspeeded button-push response. A mask occupying all eight array positions is presented after a fixed exposure duration so that subjects' accuracy in reporting the probed character depends on their success in shifting visual attention before the mask terminates perceptual processing of the displayed items.[2] In summary, the second task involves no pressure for rapid responding, but the presence of the mask makes speed of the attention shift itself critical to the level of performance achieved. In this way, we can determine whether the attention shift is postponed by processing on the first task, as is expected if the attention shift is subject to response-selection queuing. Such postponement, if it occurs, ought to show up in two ways. The first would be as a substantial deleterious effect of reducing SOA on accuracy in the second task. The second would be a strong dependency: The faster Rl is, the greater the accuracy of the second task, because the faster the first task response was selected, the higher the probability that the attention shift could occur early enough to succeed. Furthermore, the shorter the SOA, the greater the effect of the first task ought to be. In the later experiments reported in this article, additional manipulations are used both to test the assumptions underlying the methodologies used and to explore the generality of the conclusions of Experiment 1.

Experiment 1

Subjects made a rapid choice response to a tone stimulus. The tone was followed at an SOA of 50, 150, or 650 ms by a brief array of eight letters (each an A, B, C, or D), with a probe next to one of the letters. The array was followed by a

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[1] In fact, such attention shifts may nonetheless occur toward the target in visual search tasks (Hoffman, Nelson, & Houck, 1983), but there is no good reason to believe that performance in the tasks used by Pashler (1989) was dependent on them.

[2] Note that this assumption does not depend on any particular analysis of masking (e.g., interruption vs. integration), and in any case, the assumption will be specifically tested in Experiment 2.

mask. The subjects made a nonspeeded response to the probed letter, classifying it as an A, B, C, or D.

If shifting visual attention requires the same mechanism as that which carries out response selection, the reduction in SOA from 650 to 150 ought to be accompanied by a drastic reduction in second-task accuracy, and strong contingencies ought to exist between first-task speed and second-task accuracy. Furthermore, these contingencies ought to increase with shorter SOAs.

Method

Subjects. Nineteen students at the University of California, San Diego, participated as subjects in partial fulfillment of a course requirement.

Apparatus and stimuli. The stimuli were presented on Princeton Graphics SR-12 and NEC Multisync monitors controlled by IBM PC microcomputers (with Sigma Designs Color-400 and Paradise VGA color boards, respectively). The first stimulus was a tone presented through speakers at 300 or 900 Hz. The second stimulus was a centrally located display of eight letters presented in two rows of four characters. The letters were selected randomly without constraint from the set A, B, C, and D. A probe consisting of a short horizontal line was presented above or below the probed character. If the character was on the top row, the probed item was above the character, and if the character was on the bottom row, the probe was below the character. The position of the probe was selected randomly without constraint. The mask display consisted of eight Xs presented in the positions formerly occupied by the letters. The letters and masks measured about 0.3 cm width x 0.4 cm height, and the total display measured 3.9 x 3.0 cm, or 3.72° x 2.89° visual angle on the basis of a typical viewing distance of 60 cm. The probe measured 0.4 x 0.1 cm (0.38° x 0.10°), and the distance separating the probe and the probed character was 0.3 cm (0.29°). All stimuli were presented in yellowish white on a black background.

Design. The experiment was divided into 15 blocks of 30 trials each. Three different SOAs separated the tone (SI) and the letters (S2): 50, 150, or 650 ms. These were used equally often. Each block

of 30 trials thus consisted of 10 trials at each SOA, presented in random order.

Procedure. The subjects were given written instructions describing the task. The instructions stated that SI should be made as rapidly and accurately as possible, but accuracy alone was stressed on the probe task. To discourage hasty responses to S2 the program did not accept letter responses until 700 ms after the R1, requiring repetition of any premature responses. Prior to data collection, each subject worked through 72 practice trials in three miniblocks of 24 trials each. During these miniblocks, the exposure duration was longer to allow the subject to become accustomed to the task.

Figure 2 shows the procedure. Each trial began with the presentation of a plus sign as a fixation point, which appeared at the center of the display for 1000 ms. Five hundred ms after its offset, SI was presented at either 300 or 900 Hz for 150 ms. After the SOAs of 50, 150, and 650 ms had elapsed, the array of letters appeared in the center of the screen (together with the probe), and then the array was replaced with masks after the proper exposure duration. Subjects responded to S1 by pressing either the *Z* or *X* key on the keyboard (corresponding to a low or a high tone, respectively) with the first or second finger of the left hand. Subjects responded to S2 by pressing the *B, N, M,* or comma keys with the right hand (corresponding to A, B, C, or D, respectively). As soon as R2 was detected by the computer, the display of masks was terminated. If an error was made on either task, a green warning message ("ERROR!") was displayed for 750 ms, followed by a 250-ms offset. The intertrial interval between R2 and the onset of the next fixation point was 1.3 s. At the end of each block the subject rested until he or she was ready to resume. During these rest breaks, feedback was provided, which consisted of the mean correct RT for the tone task and the number of errors on both the first and second task.

The exposure duration for the letters was constant throughout a block, but it was adjusted between blocks. The initial exposure duration was 200 ms for all subjects. When accuracy on this task fell below 70% on a given block, the duration was increased by 33 ms on the next block; if it exceeded 80%, the duration was decreased correspondingly. Because SOA was manipulated within blocks, exposure duration was not confounded with the SOA between SI and S2.
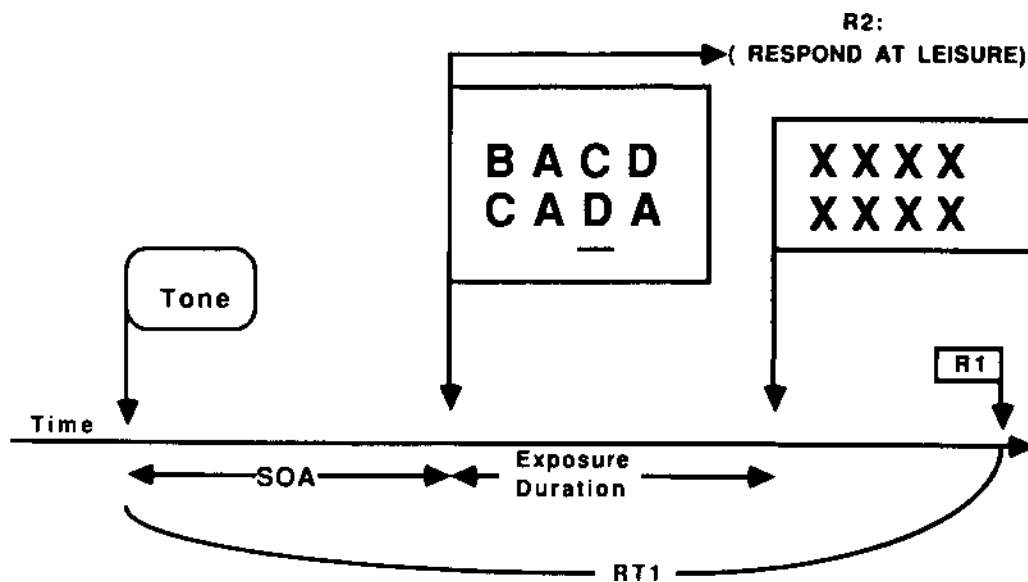

Figure 2. The procedure in Experiment 1. (Rl is speeded, and R2 is made at the subjects' leisure; depending on the stimulus onset asynchrony [SOA], the tasks may overlap extensively.)

Results and Discussion

Basic results. The data collection produced 2,850 pairs of responses for each of the three SOA conditions (19 subjects x 150 response pairs). Mean correct Rl (tone) RTs and percentage errors on the second task are presented in Figure 3 as a function of the SOA. (The scale for the error rates in the figure is the same as that used in Experiment 2; as this article proceeds, the reason for this will emerge.) For the RT analysis, Rl times under 160 ms or over 1,000 ms were discarded as deviant (6.6% of the trials). Reaction times to the tone did not differ greatly as SOA was lengthened (476, 464, and 495 ms for SO As of 50, 150, and 650 ms, respectively), although an analysis of variance (ANOVA) showed that the effect was significant, $F(2, 36) = 3.4, p < .05$.

The percentage errors in the second (probe) task were 24.3%, 23.8%, and 22.4% for the SOAs of 50, 150, and 650 ms, respectively. This effect of SOA was not significant, $F(2, 36) = 1.4, p > .20$. Across subjects, the overall mean exposure duration for the letter displays was 157 ms; for the last block, the mean was 143 ms, suggesting, not surprisingly, that some improvement on this task was taking place.

The mean percentage errors in the first (tone) task were 4.3%, 3.1%, and 2.7% for the SOAs of 50, 150, and 650 ms, respectively. This effect was significant, $F(2, 36) = 4.1, p < .05$.

Comments. The results show that the decrease in SOA from 650 ms (minimal overlap) to 50 ms (maximal overlap) produces a small and statistically nonsignificant 1.9% increase in errors in the second (probe) task. Although the effect is nonsignificant, it may be real. For present purposes, the point is merely that the effect is very small. As this article proceeds, the empirical justification will emerge for rejecting attention-shift postponement as an account of an effect of this magnitude.
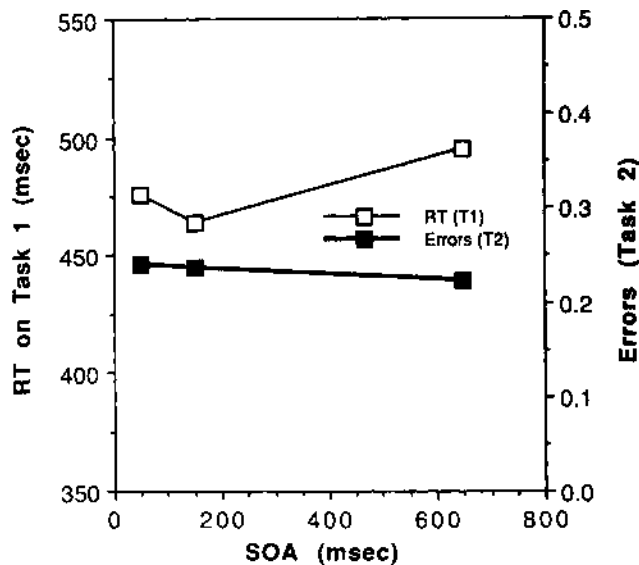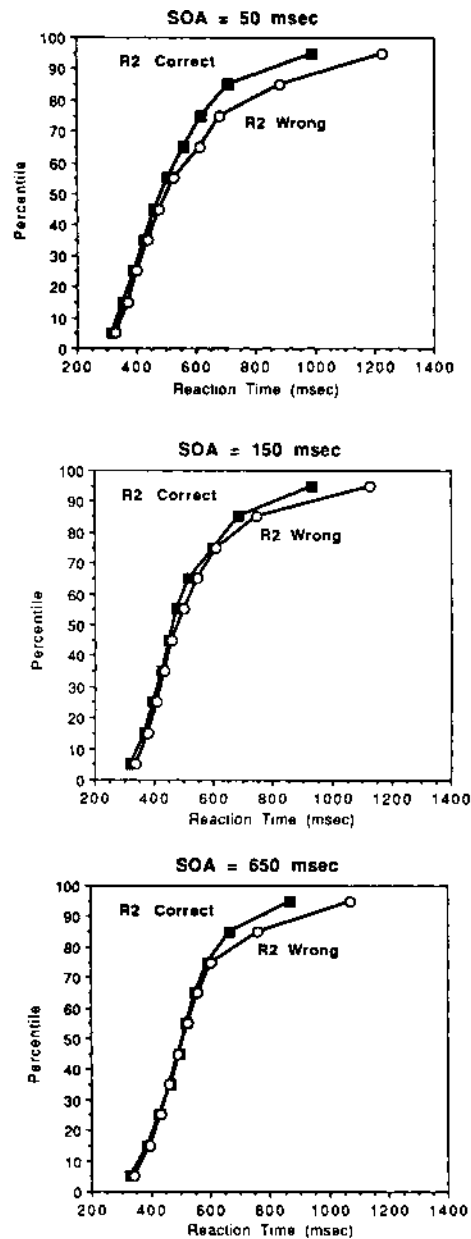

Figure 4. Experiment 1: Cumulative latency distributions for Rl as a function of stimulus onset asynchrony (SOA) and whether R2 is correct or wrong.

Figure 3. Experiment 1: Error rates on Task 2 (T2) and reaction times (RTs) on Task 1 (T1) as a function of stimulus onset asynchrony (SOA).

Reaction time distributions. To investigate further the effects on Rl latencies, the RT distributions were analyzed. First, for each subject, the approximately 150 correct RTs from each SOA condition were rank ordered, and the scores approximating the 5th, 15th, ..., 95th percentiles were estimated, by using linear interpolation when necessary. (No cutoffs were used in this analysis.) Then, these 30 percentile scores (3 SOAs x 10 percentile values) were averaged across subjects; in short, the cumulative distribution functions were Vincentized (see Thomas & Ross, 1980, for a discussion). The results are graphed in Figure 4, which shows percentile as a

function of RT for the three SOAs separately. The fact that the fastest RTs are slightly faster at the short SOAs confirms that S2 may serve as a (rather weak) accelerator of responses, thus supporting the early observations of Nickerson (1967).

Dependencies between Rl and R2 performance? As discussed in the introduction, if shifts of visual attention are subject to response-selection postponement, then variation in Rl times across trials ought to be related to variation in the accuracy of R2 on those trials. If the attention shift in the second task waits for completion of any stages of the first task, then the faster Rl is, the higher the probability that this shift will be complete before the mask brings perceptual processing to a halt. Note that this in no way depends on any idealized assumption that the mask terminates processing instantaneously.

To examine any possible dependencies, we look at the proportion of errors on R2 as a function of the relative speed of the corresponding Rl with respect to the Rl distributions. This was accomplished as follows. For each subject, all of the (approximately 150) Rl latencies were ranked and divided into five quintiles for each SOA. Then, for all of the Rl responses falling into a given quintile, the proportion of errors in the corresponding R2 responses was computed. These were averaged across subjects, and an ANOVA was performed with: SOA and Rl quintile as variables. Figure 5 shows the mean proportion of R2 errors as a function of Rl quintile, with SOA as a parameter. The graph indicates only a weak trend for slower Rls to be followed by less accurate R2s; it was nonsignificant, $F(4, 72) = 1.5$, $p > .20$. The dependencies do not increase at shorter SOAs, which is confirmed by the nonsignificant Quintile x SOA interaction, $F(8, 144) = 0.45$, $p > .80$. In Experiment 3, I examine corresponding effects for response latencies in R2, with the same tasks, in which response-selection postponement predicts very different patterns of dependencies.
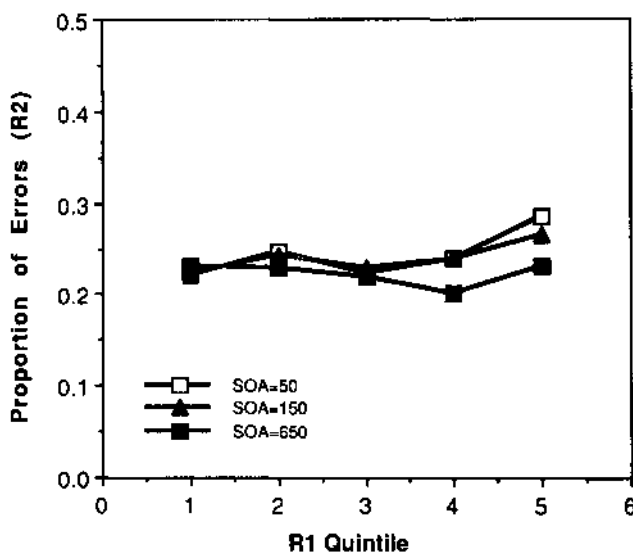

Figure 5. Experiment 1: Mean R2 accuracy as a function of the quintile in which the R1 fell within R1 distribution (for that subject x SOA [stimulus onset asynchrony]).

Summary. The results mirror findings of Pashler (1989; Experiments 1 and 2), which also examined accuracy of processing a brief masked display as a second task. In those studies, however, attention shifts were not required; only nonselective processing of the entire second display was required. The present results reject the hypothesis that the attention shift in the second display is postponed by response selection (or other stages) of the first task. If it were, a major reduction in the accuracy of the second task ought to have been observed as the SOA was cranked down to increase the overlap of the tasks. In addition, trial-to-trial variability in the Rl latency ought to have been propagated onto the R2 error rate, especially at short SOAs. This did not occur. Experiments 2 and 3 undertake to provide direct confirmation of the assumptions on which this reasoning rests.

Experiment 2

In the previous experiment, shortening the delay between the (first task) tone stimulus and the (second task) display plus probe produced a seemingly negligible effect on performance (1.9%). But what exactly counts as negligible? Theoretically, the issue is not whether the effect is truly very tiny but whether the magnitude of the effect is even approximately what ought to be expected if the shift of visual attention were subject to postponement. But how can one know how substantial the effects on accuracy would be if attention shifting were delayed? Previous investigations of masking suggest that masks rapidly terminate perceptual processing (Averbach & Coriell, 1961; Turvey, 1973). This in turn suggests that any substantial postponement of the attention shift will be very costly indeed. The stimuli and masks used by these previous investigators, however, inevitably differed in various ways from the ones used here. So how can it be determined whether a postponement of attention shift in the face of this specific masking procedure really would have produced a major decrement in accuracy?

In the present experiment, I address the question by directly assessing the costs of delaying the attention shift. This is done simply by delaying the probe itself. If a substantial delay in visual attention shifts produces a mere 1.9% cost, then the effects of probe delay ought to be of approximately that magnitude, and the 1.9% effect in Experiment 1 will be seen to be consistent with the attention-shift postponement hypothesis. To measure this, the present experiment follows the previous one except that the first (tone) task is omitted, and instead of varying SOA, the delay of the probe is varied with respect to the onset of the display.

Method

Subjects. Eleven students at the University of California, San Diego, participated as subjects in partial fulfillment of a course requirement.

Apparatus and stimuli. The apparatus was the same as that of Experiment 1. In this experiment, the only stimulus requiring response was the display of eight letters, which was identical to that in Experiment 1.

Design. There were 15 blocks of 30 trials each. Three different intervals between the display and the probe were used: 17 ms, 100 ms, and 183 ms. These were used equally often. Each block consisted of 10 trials at each probe delay, presented in random order.

Procedure. Figure 6 shows the procedure, which was basically like that of Experiment 1 except that subjects responded only to the probed character. The exposure duration was again adjusted between blocks, starting with an initial exposure duration of 200 ms for all subjects. The procedure for adjusting the duration was the same as that of Experiment 1. The probe delays were fixed, of course, and therefore for some subjects in the later blocks of trials the 183-ms probe could occur after the mask.

Results and Discussion

Basic results. The data collection produced 1,650 pairs of responses for each of the three SOA conditions (11 subjects x 150 response pairs). The mean proportion of errors on the second task is presented in Figure 7 as a function of the probe delay. The figure is plotted on the same sale as the errors for Experiment 1. An ANOVA showed that the effect of probe delay was significant, $F(2, 20) = 140.3$, $p < .001$.

Summary. Delaying the probe by 167 ms has a disastrous effect on performance—a 30% increase in errors. This is observed with the same task, displays, and masking manipulation as are used in Experiment 1, and it supports the findings and interpretations of Averbach and Coriell (1961) and Pash-ler (1984a) with respect to masking. The result tells us that if the attention shift in the second task of Experiment 1 had been subject to any substantial postponement (say, 100 ms, or even 25 ms), then a decrement much larger than the 1.9% effect in Experiment 1 ought to have been observed. Experiment 3 looks at the dual-task situation of Experiment 1 in a way that allows the extent of response-selection delays to be assessed directly, to complete the case.
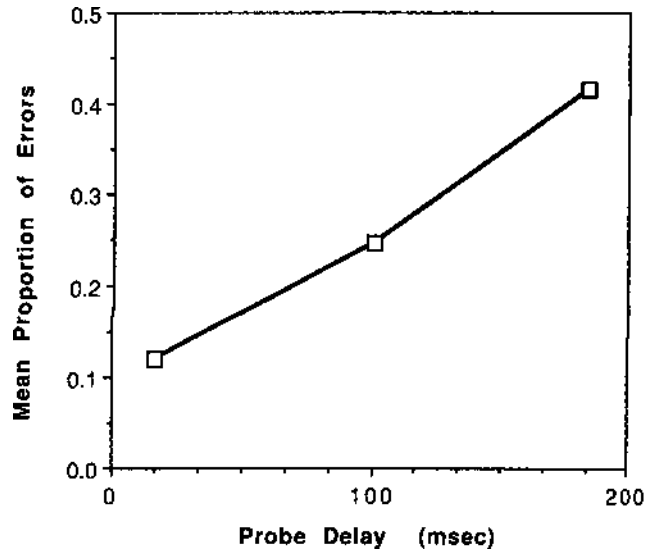

Figure 7. Experiment 2: Mean R2 accuracy as a function of probe delay.

Experiment 3

The two-component model (Pashler, 1989) asserts that a single central attentional mechanism is required whenever selection on two tasks must occur simultaneously, generating postponement of second-task response selection whenever first task responses are generated. In Experiment 1, the second task required an attention shift but not immediate response selection because the subjects were encouraged to make the second response at their leisure. For this reason, the results of that study simply cannot confirm that response selection is subject to postponement, or do they give any estimate of the
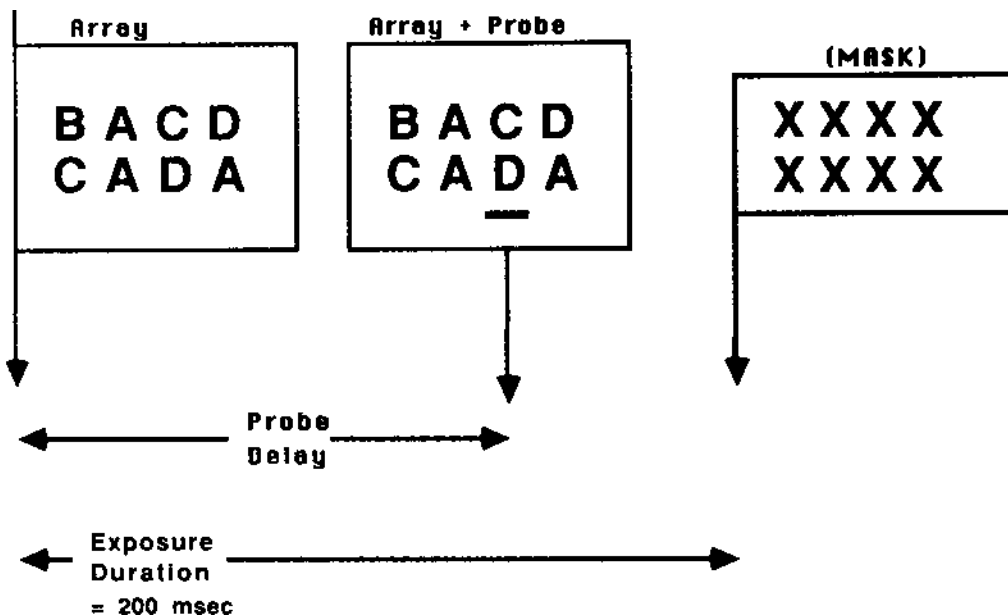

Figure 6. The procedure in Experiment 2. (Probe delay is varied, whereas mask delay is fixed at 200 ms.)

duration of that postponement. For that reason, we do not know how long attention shifts would have been postponed, were they subject to the same form of postponement as response selection. According to the two-component model, however, we can invoke response-selection postponement and measure its duration simply by modifying the same task to require an immediate response. Then, response-selection postponement ought to show up as an SOA-dependent increase in R2 latencies. Experiment 3 therefore followed Experiment 1, except that (a) subjects were required to make both responses as quickly as possible, (b) masks were eliminated, and (c) the display of letters (S2) remained present until response.

Method

Subjects. Thirteen students at the University of California, San Diego, participated as subjects in partial fulfillment of a course requirement.

Apparatus, stimuli, and design. These were like those of Experiment 1, with a few exceptions. First, there were no masks. Second, the display of letters remained present until subjects had responded to the probed letter.

Procedure. The procedure was like that of Experiment 1, except for the instructions, which told subjects to respond as rapidly as possible to SI and then as rapidly as possible to S2. The experimenter monitored the subjects during the practice to discourage any "grouping" of responses (for a discussion of grouping, see Borger, 1963; Pashler & Johnston, 1989).

Results

Basic results. The data collection produced 1,950 pairs of responses for each of the three SOA conditions (13 subjects x 150 response pairs). Mean RTls and RT2s are presented in Figure 8 as a function of the SOA. For this purpose, RTls under 160 ms or over 1,000 ms, and RT2s under 200 ms or over 2,500 ms were discarded as deviant (3.67% of trials). Mean RTls to the tones were 529 ms, 499 ms, and 477 ms, for SOAs of 50, 150, and 650 ms, respectively. This SOA effect was significant, $F(2, 24) = 13.9$, $p < .001$. The mean RTs to the probed letter (S2) were 935 ms, 842 ms, and 747 ms for the three SOAs. This was significant, $F(2, 24) = 127.9$, $p < .001$. The percentage errors in the second (probe) task were 3.2%, 3.4%, and 3.4%, for the SOAs of 50, 150, and 650 ms, respectively. This effect of SOA was not significant, $F(2, 24) = 0.07$, $p > .90$. The mean percentage errors in the first (tone) task were 1.8%, 1.5%, and 0.8%, for the SOAs of 50, 150, and 650 ms, respectively. This effect was not significant, $F(2,24) = 2.0$, $p > .15$.

Dependencies between Rl and R2 performance? As in Experiment 1, the relationship between R2 performance and Rl speed was examined. Again, the Rl latencies were divided into five quintiles. For all of the Rls falling into a given quintile, the average latencies for the corresponding R2s were computed. Figure 9 shows mean R2 speed as a function of Rl quintile, with SOA as a parameter. The results show an unmistakable dependency of R2 speed on Rl speed. The effect of Rl quintile is significant, $F(4, 48) = 87.1$, $p < .001$. Furthermore, the effect is much greater for the shorter SOAs. The Quintile x SOA interaction is significant, $F(8, 96) =$
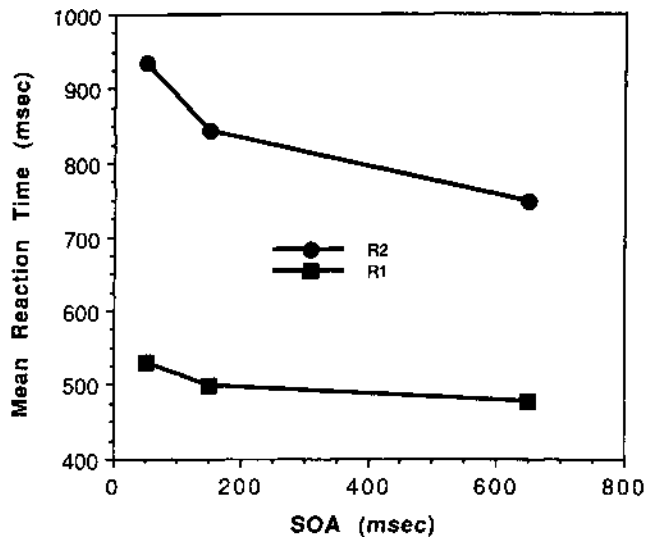

Figure 8. Experiment 3: Mean RTls and RT2s as a function of stimulus onset asynchrony (SOA).

36.1, $p < .001$. Finally, note the fine grain of this interaction: as the response-selection postponement hypothesis (see Figure 1) predicts, the shorter the SOA, the farther down into the Rl distribution is the point at which the R1-R2 latency dependency begins.

Summary. The results show that a requirement for speeded second-task response in the paradigm of Experiment 1 produces the entire pattern of effects predicted by the two-component theory. The theory states that the response selection on the second task must always wait for response selection on the first task. Therefore, reduction of the SOA produces a dramatic increase in R2 latencies. Furthermore, the distinctive pattern predicted for the dependency of R2 latency on Rl latency was confirmed in detail. The only anomalous detail is the modest slowing of Rl as the SOA is reduced.
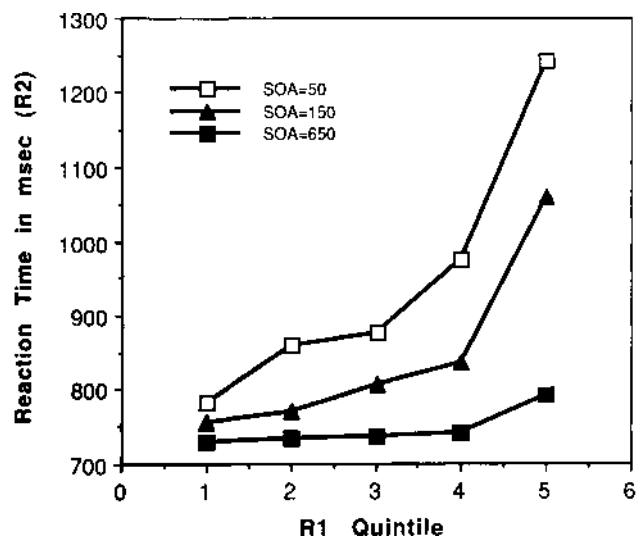

Figure 9. Experiment 3: Mean R2 latency as a function of the quintile in which the Rl fell within Rl distribution.

This is common in PRP experiments and may reflect an occasional tendency for subjects to group the two responses at short SOAs (see Pashler & Johnston, 1989), although the instructions in this experiment must have been largely successful in discouraging this.

Experiments 1-3: Discussion

Experiments 1-3 have examined subjects' performance in making a choice response to a probed letter in a display of eight letters. When the response was unspeeded, and the display followed on the heels of a choice RT task to a tone, SOA reduction had only a very small effect on second-task accuracy (this is the 1.9% difference observed in Experiment 1). Under these circumstances, the dependence of R2 accuracy on the speed of R1 was minimal and not affected by SOA. In Experiment 2, the first task was eliminated, and the probe itself was delayed for a variable interval after the onset of the letter display. This allowed the effect of delaying the attention shift itself to be examined. A 167-ms delay produced about a 30% reduction in accuracy.

Therefore, the 1.9% effect of SOA in Experiment 1 cannot reflect postponement of the attention shift, unless the duration of this postponement is extremely short. If the attention shift required the same mechanism as the response-selection stage, then the duration of this postponement would be comparable to the duration of postponement of response selection in a task in which both responses are speeded. To complete the case that the attention shift is not subject to the same sort of postponement as R2 selection, a measure of the SOA-induced slowing of an overt speeded R2 is required. This is provided by the results of Experiment 3, which used the same tasks as Experiment 1 but with the second (probe) display unmasked and R2 speeded. Here, the SOA reduction from 650 to 50 ms (which produced tiny effects on R2 accuracy in Experiment 1) yielded a 188-ms slowing in R2. The SOA reduction alone from 150 to 50 ms cost subjects 93 ms in R2 slowing, which suggests that a stage in the second task was postponed on virtually all trials over this SOA range. Previous research all indicates that this stage is response selection (Pashler, 1984b, 1990; Pashler & Johnston, 1989).

At this point, the results of all three experiments work together to reject decisively the hypothesis that attention shifts require the central mechanism responsible for response-selection queuing. The results of Experiment 2 tell us that a delay of 167 ms in using the probe costs 30% in accuracy, and the results of Experiment 3 tell us that the SOA reduction in the dual-task paradigm induces a postponement of response selection that is greater than 167 ms. If the attention shift were postponed along with response selection, then the 1.9% increase in error rates induced by SOA reduction in Experiment 1 ought to have been more than an order of magnitude greater in size. Therefore, visual attention shifts in this paradigm do not wait for the response-selection mechanism to be freed from the first task.

The results of Experiment 3 also add new support to the response-selection queuing hypothesis. Dependencies between R2 speed and R1 speed are dramatic, with slower R1s associated with slower R2s. The details of these dependencies

are just as the postponement model predicts: greater dependencies with shorter SOAs and dependencies that begin farther and farther down the R1 distribution as SOA is reduced.

Experiment 4

A number of assumptions and conclusions reached above can be subjected to a further check by examining the effects of an additional manipulation that involves the timing of the probe. Experiment 4 uses the dual-speeded-response paradigm of Experiment 3, but on half of the trials, the probe is presented 100 ms earlier than the array (preprobe condition), and on the other half of the trials, the probe is presented at the same time as the array (simultaneous condition, as in Experiments 1 and 3). The R2 latency is always measured from the array onset.

According to the assumptions and conclusions made above, the effects of this preprobing manipulation ought to vary depending on SOA. At the long SOA, it is assumed that the first task is essentially complete when the second task commences. It has also been assumed that when the probe appears in this condition, an attention shift begins immediately, which induces selective readout for the probed item and then classification of this item, response selection, and response execution (see also Pashler, 1984a, for further analysis of this sequence of events). Given these assumptions, preprobing at the long SOA ought to lead to a speedup of RT2 (measured from the array onset) of a duration equal to the duration of preprobing (i.e., SOA between probe and array). The account also plainly predicts no effects of preprobing on R1 latencies.

Now consider the short SOA conditions. Here, the model again predicts no effects of preprobing on R1 latencies, because nothing in R1 is assumed to wait for anything in S2—the probe included. The predicted behavior of R2 is more interesting, however. At the short SOAs, R2 selection must wait for the completion of R1 selection. The results of Experiments 1-3 indicate that the attention shift necessary for generating R2 does not wait for selection of R1, however. Therefore, the time at which this probe-dependent shift commences will have no effect on the RT measured from the probe to R2. This is the logic of the chronometric studies reviewed in the introduction (Pashler, 1984b; Pashler & Johnston, 1989). In short, the assumptions and conclusions advocated above predict that the effect of 100-ms preprobing on R2 latencies ought to decrease from roughly 100 ms at the longest SOA to roughly 0 ms at the shortest SOA. Obviously, this idealizes things a bit, because variability in the duration of these various mental events will mean that postponement will occasionally occur at the longest SOA, and it will occasionally be averted at the shortest SOA. So what the model predicts is strong underadditivity of SOA and preprobing on R2 latencies.

Note also that this experiment, unlike the preceding three studies, cannot refute a model that postulates response-selection postponement but says that attention shifts are subject to this postponement. This is because if attention shifts were postponed along with response selection, the preprobe would still not be used until the same time as the simultaneous probe, thus eliminating effects of when the probe arrived.

Although the experiment cannot specifically refute that hypothesis (rejected by the previous studies in any case), it provides an opportunity to test simultaneously for a range of other possible violations of our assumptions.

Method

Subjects. Twelve students at the University of California, San Diego, participated as subjects in partial fulfillment of a course requirement.

Apparatus and stimuli. These were all precisely like those of Experiment 3.

Design and procedure. The design and procedure was like that of Experiment 3, except for an extra condition pertaining to the timing. On half of the trials, the probe preceded the display of characters by 100 ms, and on the other half of the trials, they were simultaneous. This factor was manipulated within block, along with SOA. Thus, for each of the six SOA x Probe Timing conditions, there were five trials per block and 75 observations per subject over the entire experiment, which again consists of 15 blocks.

Results and Discussion

Basic results. The data collection produced 900 pairs of responses for each of the three SOA conditions (12 subjects x 75 response pairs). Mean latencies for Rl (tone) and R2 (letter) are presented in Figure 10 as a function of the SOA. As in Experiment 3, RTls under 160 ms, or over 1,000 ms were discarded as deviant (9.5% of trials) along with RT2s under 200 ms and over 2,500 ms. The RTs to the tone were reduced somewhat as the SOA was lengthened (577 ms, 557 ms, and 527 ms for the SOAs of 50, 150, and 650 ms, respectively), and the effect was significant, $F(2, 22) = 12.0$, $p < .001$. Responses were 9 ms slower on average with the preprobe condition; this was not quite significant, $F(1, 11) = 3.5$, $.05 < p < .10$. The Probe Timing x SOA interaction was not significant.
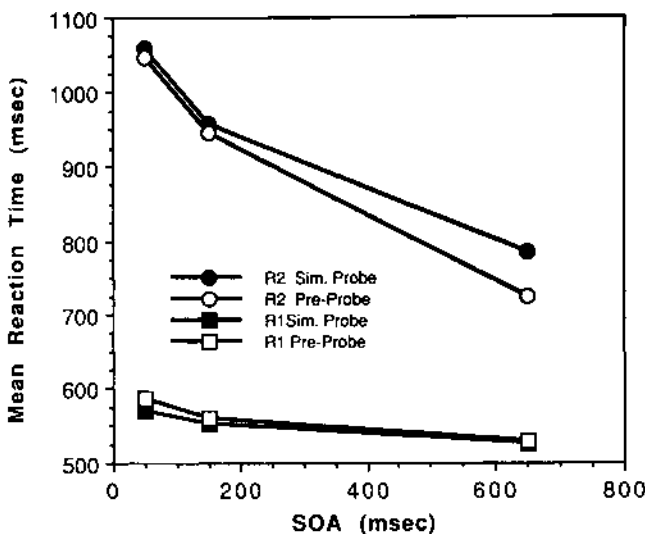

Figure 10. Experiment 4: Mean for RTls and RT2s as a function of stimulus onset asynchrony (SOA) and whether probe preceded display (preprobe) or was simultaneous (sim. probe).

In the first (tone) task, the percentage errors were 2.5%, 1.6%, and 0.9% for the SOAs of 50, 150, and 650 ms, respectively. This difference was significant, $F(2, 22) = 4.1$, $p < .05$. In the preprobe condition, the error rate was 2.2%, compared with 1.2% in the simultaneous condition; this effect was also significant, $F(l, 11) = 7.3$, $p < .05$. The two did not interact significantly.

In the second (letter) task, the mean RTs were 1,053, 952, and 755 ms for the three SOAs, respectively. This PRP effect was significant, of course: $F(2,22) = 73.4$, $p < .001$. Responses were faster overall in the preprobe condition (906 ms) than in the simultaneous condition (934 ms). This main effect was significant, $F(l, 11) = 20.8$, $p < .002$. The advantage for the preprobe condition was 79 ms for the 650-ms SOA, 13 ms for the 150-ms SOA, and 7 ms for the 50-ms SOA. The interaction of SOA with the preprobe versus simultaneous conditions was significant, $F(2, 22) = 7.9$, $p < .005$.

The error rates for the letter task were not significantly affected by any of the variables, although there was a trend toward lower error rates for the preprobe condition (2.4%) than for the simultaneous condition (3.4%), $F(1, 11) = 4.7$, $.05 < p < .10$.

Discussion

In the simultaneous probe condition, the RT effects parallel those of Experiment 3 closely, as well they should, because the simultaneous probe condition basically replicates Experiment 3. Overall, RTs are somewhat slower, but the basic PRP effect (R2 slowing as SOA decreases) is as expected. The prediction that preprobing ought to have no effect on Rl latency is borne out statistically, although there is a trend toward a very small slowing of Rl in the preprobe condition. This may reflect occasional disruption of the first task by the earliest S2 events.

Of primary interest is the prediction that the benefit in R2 speed when the probe comes early (preprobe condition) ought to be reduced as the SOA is shortened, because of the postponement of processing stages that follow the attention shift in the S2 display. The idealized nonstochastic version of the model predicted that the effect ought to be reduced from 100 ms to 0 ms. In the data, the effect goes from about 80 ms at the long SOA to under 10 ms at the shortest SOA, and the interaction is significant. The departure of these numbers from the predictions is in the range to be expected given the variability in the underlying component durations. In summary, then, this experiment clearly supports the assumptions and conclusions of the previous three experiments.

Experiment 5

The previous experiments indicate that although response selection on a second task is postponed by processing on the first task, shifting visual attention in response to a probe is not subject to such postponement and therefore does not depend on the central mechanism that is required for response selection. This might indicate that control over visual attention never depends on this mechanism. Alternatively, it might be that the independence occurs only under a restricted range

of conditions. In the previous studies, attention shifts were induced by an especially natural and compatible relationship between the probe and the probed item; namely, the probe was a visual transient directly adjacent to the item to be attended to, and there were no competing items in the display that were as close to the probe as the correct item. Why should this matter? There are claims in the literature that shifts in visual attention directly toward the region occupied by a transient event in the visual field occur automatically. Jonides (1981) found that the effect of cues of this type was not easily suppressed even when they were mostly invalid, and neither were the effects reduced when subjects held onto a concurrent memory load. By contrast, the cuing effects of a centrally located arrow that pointed toward the cued item were partially suppressed by memory loads or under conditions of poor validity. (Similar distinctions were examined by Posner, 1980, and Miller & Rabbitt, 1989.) In fact, there is no reason to believe that holding onto a memory load actually occupies the central mechanism of response selection, even though it is often assumed to draw on so-called *central capacity* (see Pashler, 1984b, for a critical discussion of that concept). Therefore, Jonides's results cannot address the basic questions posed at the outset of this article; however, they do suggest that the results discussed above might be restricted to peripheral transient stimuli.

Experiment 5 therefore repeated the design of Experiment 1 but compared two kinds of cues: a peripheral cross just eccentric to the probed item and a central arrow pointing toward the probed item. The different types of cues were presented in different blocks.

Method

Subjects. Nineteen students at the University of California, San Diego, participated as subjects in partial fulfillment of a course requirement.

Apparatus and stimuli. The equipment was as in the previous experiments, except that Paradise VGAPlus color cards were used in graphics mode. The displays were circular arrays of eight letters from the set A, B, C, and D. The diameter of the circle was 7.5 cm (7.1°). Each letter was 1.2 cm width (1.15°) x 2.5 cm height (2.4°). The peripheral probe consisted of a cross (1 cm x 0.6 cm) just eccentric to the probed letter. The central probe was an arrow 3 cm long in the center of the display.

Design. There were 16 blocks, each consisting of 30 trials. Half of the blocks were peripheral probe blocks, and half were central probe blocks; the types of blocks alternated. Within each block, there were equal numbers of trials at the three SOA: 50, 150, and 650 ms.

Procedure. The procedure was like that of Experiment 1 except that subjects were required to respond to the item that the arrow pointed to (in central cue blocks) or to the item adjacent to the probe (in peripheral cue blocks).

Results and Discussion

Basic results. The data from 4 subjects were excluded because their error rates were close to chance. In two cases, this resulted from pressing the wrong set of response keys. Mean RTls (tone) and R2 error rates as a function of SO A and probe type are presented in Figure 11. The RTls that
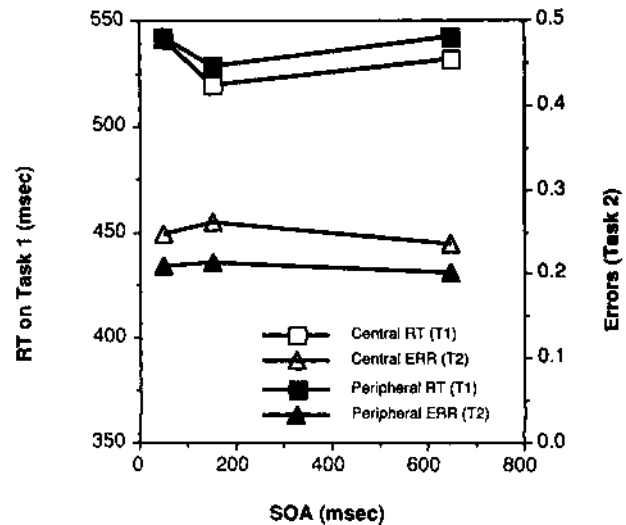

Figure 11. Experiment 5: Mean RT1 s and errors on R2 as a function of stimulus onset asynchrony (SOA) and probe type (peripheral vs. central).

were under 150 ms or over 1,000 ms were discarded as deviant. Neither probe type nor SOA significantly affected the RTls. The SOA effect was nonsignificant, $F(2, 28) = 1.2$, $p > .30$.

The percentage errors in the second (probe) task were 22.9%, 23.8%, and 21.9%, for the SOAs of 50, 150, and 650 ms, respectively. The SOA effect was not significant, $F(2, 28) = 0.6$, $p > .55$. There were more errors with the central probe (24.7%) than with the peripheral probe (21.0%), although the effect was not quite significant, $F(1, 14) = 3.6$, $p > .05$. (Note that this is not very interesting in any case because exposure duration was adjusted separately for the two probe types.) The Probe Type x SOA interaction was not significant, $F(2, 28) = 0.13$.

The mean percentage errors in the first (tone) task were 17.3%, 13.2% and 11.2% for the SOAs of 50, 150, and 650 ms, respectively. This effect was significant, $F(2, 28) = 3.5$, $p < .05$.

Comments. The results show that the decrease in SOA from 650 ms (minimal overlap) to 50 ms (maximal overlap) still produces only a very small effect on accuracy in the second (probe) task. There is no hint that the use of central (nonautomatic) cues suffers any greater interference from the tone task than does the use of peripheral (nonautomatic) cues.

Dependencies between Rl and R2 performance? The relationship between R2 accuracy and Rl speed was examined as in Experiment 1. In Figure 12 the top panel shows the R2 accuracy as a function of Rl quintile, with SOA as a parameter, for the central cues, and the bottom panel shows the corresponding data for the peripheral cues. Overall, R2s are not significantly more accurate when Rl is fast. Dependencies were not significantly stronger with central probes, and as in previous experiments, no interactions involving SOA were significant (all Fs < 1). Thus, the data strongly imply that whatever type of probe is used, the first task and the attention shift operate independently, with very slight positive correla-
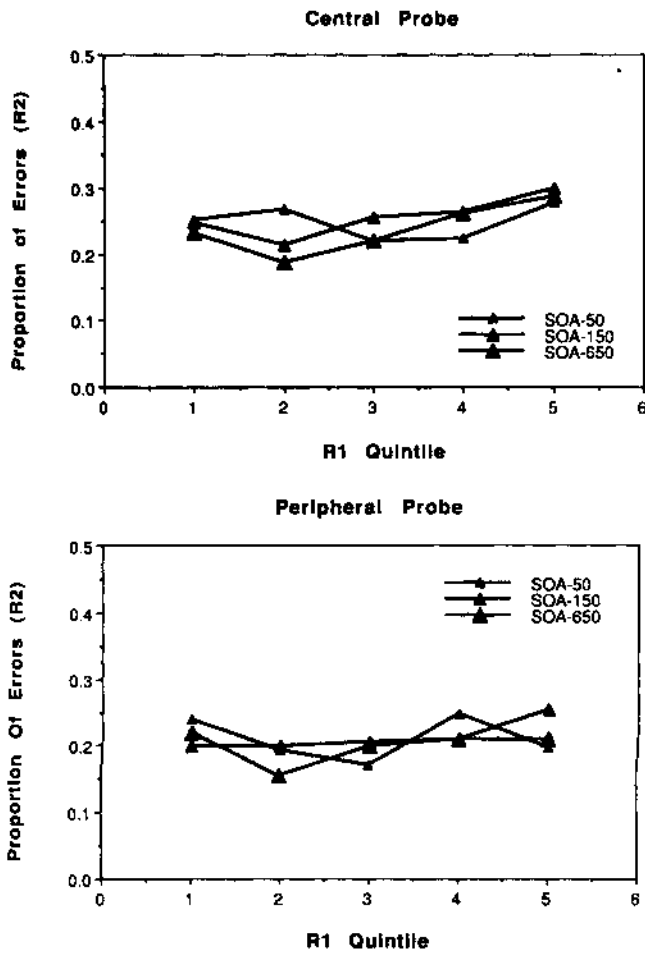
Central Probe

Peripheral Probe

Figure 12. Experiment 5: Mean errors on Task 2 as a function of the quintile in which the R1 fell within the R1 distribution, for central probe (top) and peripheral probe (bottom).

tions between performance on the two tasks induced by trial-to-trial variations in preparation for the entire ensemble of tasks.

Summary. The use of central, symbolic cues did not change the results observed in Experiment 1. There is no sign that shifts of attention induced by these cues wait for completion of processing stages in the first task any more than shifts induced by peripheral cues.

Experiment 6

The previous experiments show that although response selection on the second task is postponed by processing on the first task, shifting visual attention in response to a probe is not subject to such postponement and therefore does not depend on the central mechanism that is required for response selection. The results of Experiment 5 show that this is not restricted to the case of automatic attention shifts induced by a peripheral transient. The present experiment extends this result to look at attention shifts that are directed directly away from peripheral transient visual events. This seems like a

mode of cuing likely to represent the most extreme nonautomatic attention shift. The displays and cues were presented as in Experiment 1, but subjects were required to respond to the item opposite the probe rather than adjacent to it.

Method

Subjects. Nineteen students at the University of California, San Diego, participated as subjects in partial fulfillment of a course requirement.

Apparatus, stimuli, and design. These were as in Experiment 1.

Procedure. The procedure was like that of Experiment 1 except for two differences. First, the subjects were required to respond to the item that was opposite the probe rather than next to it. Thus, if the probe was above the third item on the top row, subjects were to report the third item on the bottom row, and if the probe was below the first item on the bottom row, subjects were to report the first item on the top row. Second, the initial exposure duration was 250 ms rather than 200 ms; pilot work suggested that roughly this amount of extra exposure duration was required to achieve a comparable level of performance.

Results and Discussion

Basic results. The data from 2 subjects had to be thrown out because of a complete failure to follow the instructions: These subjects delayed their first responses, *actually managing* to produce very few responses that were even within the 1-s Rl cutoff. The remaining data collection yielded 2,550 pairs of responses for each of the three SOA conditions (17 subjects x 150 response pairs). Mean RTls (tone) and percentage errors on the second task are presented in Figure 13 as a function of the SOA. For this purpose, RTls under 160 ms or over 1,000 ms were discarded as deviant (5.3% of trials). The RTls did not differ greatly as SOA was lengthened (443, 435, and 453 ms for the SOAs of 50, 150, and 650 ms, respectively), although this SOA effect was significant, $F(2, 32) = 7.5, p < .005$.
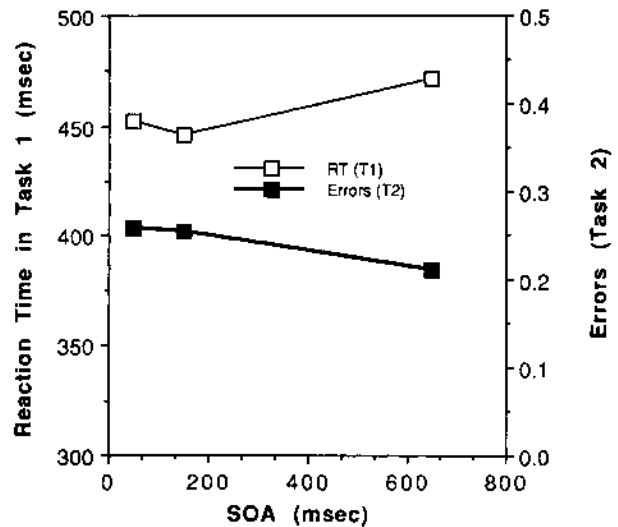

Figure 13. Experiment 6: Errors on Task 2 and reaction times (RTs) on Task 1 as a function of stimulus onset asynchrony (SOA).

The percentage errors in the second (probe) task were 26.5%, 25.7%, and 21.3% for the SOAs of 50, 150, and 650 ms, respectively. This SOA effect was significant, $F(2, 32) = 10.0$, $p < .001$. Across subjects, the mean exposure duration for the letter displays was 244 ms; for the final block, the average was 231 ms.

The mean percentage errors in the first (tone) task were 6.5%, 4.6%, and 3.8% for the SOAs of 50, 150, and 650 ms, respectively. This effect was significant, $F(2, 32) = 5.6$, $p < .01$.

Comments. The results show that the decrease in SOA from 650 ms (minimal overlap) to 50 ms (maximal overlap) still produces a rather small effect (5.1%) on accuracy in the second (probe) task. The effect is significant here, however, and it seems distinctly larger than that of Experiment 1. At the same time, however, the effect is still very much smaller than that expected if this nonautomatic attention shift were waiting for first-task processing stages, given the results of Experiments 2 and 3. Therefore, the analysis of dependencies between tasks ought to be especially illuminating.

Dependencies between R1 and R2 performance? The relationship between R2 accuracy and R1 speed was examined as in Experiment 1. Table 1 shows the R2 accuracy as a function of R1 quintile, with SOA as a parameter. As in the Experiment 1, there are slightly more accurate R2 responses when R1 is fast, but again the trend is quantitatively small. It is, however, significant, $F(4, 64) = 8.8$, $p < .001$. Nonetheless, the most revealing fact is that the dependency does not increase when the SOA is shortened; thus the SOA x Quintile interaction is nonsignificant, $F(8, 128) = 1.1$, $p > .30$. To put it differently: Although R2 is more accurate when R1 was fast, this is just as true when the tasks are timed so that they are usually not even overlapping in time.

Summary. Requiring subjects to make an unnatural shift of attention in this experiment made the second task harder. The exposure durations required to achieve about the same level of performance are roughly 90 ms longer. Compared with Experiment 1, a somewhat larger effect of temporal overlap on second-task accuracy has appeared. Nonetheless, the size of this effect is still much smaller than what would be expected if the shift were postponed along with response selection. On the basis of the results in Experiments 2 and 3, a decrement at least six times as large would be expected. The results of the dependency analysis provide an even clearer case against postponement of the attention shift. There is a

weak dependency between R1 speed and R2 accuracy, but this effect is modest (e.g., it is by any measure far weaker than the dependency of R2 speed on R1 speed in Experiment 3). Most critical, however, is the fact that this modest dependency is unaffected by SOA. Essentially, the contingency is just as great when the tasks rarely overlap (650-ms SOA condition) as it is when they are heavily overlapped. If it were caused by postponement, it would increase as SOA is reduced, just as the dependency of R2 speed on R1 speed in Experiment 3 did in a dramatic fashion.

In summary, the results of this experiment indicate that attention shifts are free from central postponement even when they are not induced by transients immediately adjacent to the probed items. This result seems especially surprising because these conditions may have required actual suppression of the automatic tendency (this was noted by Jonides, 1981) for attention to shift toward the cue. This observation points toward a possible interpretation of several otherwise unexplained results. Suppose first that the suppression of this automatic attention-grabbing by the probe does not require the response-selection mechanism itself, as the results here have demonstrated. Suppose furthermore that this suppression is nonetheless highly dependent on the effectiveness with which the subject has prepared for the task—concretely, how much care the subjects have taken to "remind themselves" of the need to shift away from rather than toward the cue. Finally, suppose, as has been suggested before (e.g., see Logan, 1978; Pashler, 1984b), that holding a memory load is not a genuine dual-task situation in the sense of being a task that requires constant mental activity, but rather, suppose that it is simply a very effective way to disrupt advance preparation for a concurrent task. In that case, Jonides's findings that the nonautomatic cuing is subject to greater memory-load effects than the automatic cuing follows naturally. And what of the rather larger dependencies of R2 accuracy on R1 speed observed in this experiment? Such weak but nonzero dependencies have previously (Pashler, 1989) been attributed to a correlation in the preparation of the two tasks. If this is correct, it could explain why the dependency ought to be magnified in Experiment 5, given the need for extra preparation posited above. It is also consistent with the fact that the dependency does not interact with SOA.

This account does not explain that the SOA effects on R2 accuracy appear to be somewhat larger here than in the other experiments (although they are still modest in comparison to

Table 1

Proportion of Second-Task Errors as a Function of Quintile and Stimulus Onset Asynchrony: Experiments 6 and 7

| | Stimulus onset asynchrony | | | | | |
| | Experiment 6 | | | Experiment 7 | | |
Quintile	50	150	650	50	150	650
1	0.234	0.212	0.203	0.257	0.228	0.208
2	0.227	0.266	0.189	0.259	0.273	0.205
3	0.281	0.231	0.171	0.239	0.249	0.230
4	0.269	0.271	0.235	0.212	0.256	0.186
5	0.320	0.309	0.275	0.327	0.270	0.226

the effects of delaying the probe itself). Beyond rejecting dependence of attention shifts on the mechanism responsible for response-selection postponement as a possible explanation, there simply are not many clues about the source of this residual effect. One could easily multiply possibilities, however. For example, perhaps the system responsible for postponement of response selection and other cognitive actions (see the introduction) actually does take charge of certain difficult visual attention shifts—but only on very occasional trials! Another alternative is some form of weak mutual inhibition that slightly impairs the efficiency of difficult attention shifts when they overlap first-task processing. One could empirically analyze these possibilities, of course, but the effect sizes are so small that the issues might not be resolvable with current methods, and in any case these issues seem to be of less fundamental interest than the first-order questions of where full-scale postponement does and does not occur.

Experiment 7

The previous experiments have demonstrated with converging approaches that visual attention shifts are not subject to the postponement that affects second-task response selection, even when the shifts required orienting to a location different from that of the probe itself. Experiment 7 extends this to selection on the basis of a different attribute: color. Previous research has demonstrated that selection by color is quite efficient, although not so efficient as selection by location (von Wright, 1968). In this experiment, selection by color is required, but the displays are presented with each item in a different color, which prevents the task from degenerating into selective attention to the item of a unique color. Thus, Experiment 7 examines a different form of nonautomatic attention shift, in the sense of Jonides (1981).

Method

Subjects. Thirteen students at the University of California, San Diego, participated as subjects in partial fulfillment of a course requirement.

Apparatus, stimuli, and design. These were all like those of Experiment 1, with a few exceptions. First, there were no bar markers. Second, all of the letters in the array were presented in different colors. The colors used were red, magenta, brown, light blue, yellow, and white, and the target color was green. The assignment of colors to positions was random, without replacement.

Procedure. The procedure was like that of Experiment 1 except for two differences. First, the subjects were required to respond to the identity of the unique green item in the display. Second, the initial exposure duration was 200 ms.

Results and Discussion

Basic results. The data collection produced 1,650 pairs of responses for each of the three SOA conditions (13 subjects x 150 response pairs). Mean RTls (tone) and percentage errors on the second task are presented in Table 1 as a function of the SOA. For this purpose, RTls under 160 ms or over 1,000 ms were discarded as deviant (5.2% of trials). The RTls

did not differ greatly as SOA was lengthened (452, 446, and 471 ms for the SOAs of 50, 150, and 650 ms, respectively). This SOA effect was not significant, $F(2, 24) = 2.0, p > .10$.

The percentage errors in the second (probe) task were 25.9%, 25.4%, and 21.1% for the SOAs of 50, 150, and 650 ms, respectively. This effect of SOA was significant, $F(2, 24) = 8.5, p < .005$. Across subjects, the mean exposure duration for the letter displays was 164 ms, for the final block, the average was also 164 ms.

The mean percentage errors in the first (tone) task were 6.7%, 5.6%, and 4.5% for the SOAs of 50, 150, and 650 ms, respectively. This effect was significant, $F(2, 24) = 3.4, p < .05$.

Comments. Overall, the results look very similar to those of Experiment 1, even though the attention shift could not be accomplished simply by orienting to a unique transient in the visual field. The results show that the decrease in SOA from 650 ms (minimal overlap) to 50 ms (maximal overlap) produces a small effect (4.7%) on accuracy in the second (probe) task.

Dependencies between Rl and R2 performance? As in Experiment 6, the relationship between R2 accuracy and Rl speed was examined. Figure 14 shows mean R2 accuracy as a function of Rl quintile, with SOA as a parameter. As in Experiment 6, there are slightly more accurate R2s when Rl is fast, but again the trend is quantitatively small. In this case, the Rl quintile effect is not significant, $F(4, 48) = 2.0, p > .10$. Again, the most revealing point is that the quintile dependency does not become stronger when the SOA is shortened; thus, for the SOA x Quintile interaction, $F(8, 96) = 1.2, p > .25$.

Summary. Requiring subjects to shift attention on the basis of color rather than location made the second task only slightly more difficult. The important result of this experiment, however, can be simply stated: The findings of Experiment 1 generalize to attention shifts on the basis of color. (As noted earlier, these attention shifts were not directed
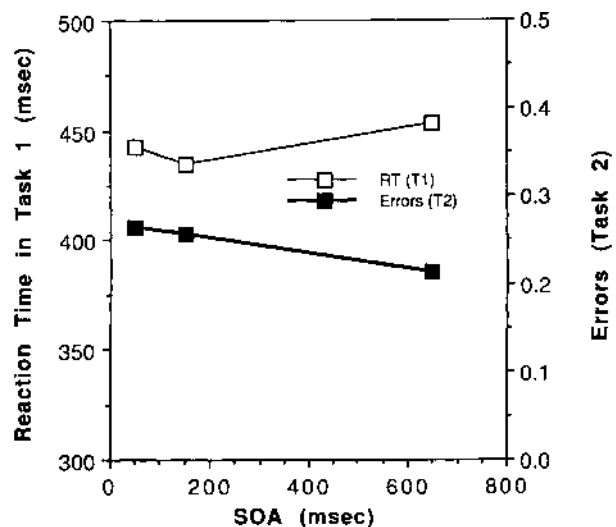

Figure 14. Experiment 7: Errors on Task 2 and reaction times (RTs) on Task 1 as a function of stimulus onset *asynchrony (SOA).*

toward a unique popout element in the display because all of the items in the display were different in color.)

General Discussion

The results of Experiments 1-7 demonstrate that although shifting visual attention may be regarded for certain purposes as a form of internal response (e.g., see Sperling & Reeves, 1980), it can nonetheless be performed concurrently with selection of unrelated motor responses. The simplest and most obvious interpretation of these results is that although there is only a single mechanism responsible for the selection of motor responses, this mechanism is not necessary for control over the focus of visual attention. This freedom from queuing in a dual-task context is not restricted to shifts of visual attention directly toward transients in the visual field—shifts that have been reported to function automatically in certain respects (Jonides, 1981). From the present results, it appears that attention shifts can be triggered autonomously from other ongoing cognitive activities in response to seemingly arbitrary visual events. Of course, further research may yet find some limits to this autonomy.

In the introduction, several reasons were mentioned why one might have expected to find that attention shifts would rely on central response-selection mechanisms and thus be subject to queuing in the dual-task situation. Posner et al. (1989) reported evidence that what they termed the *anterior attention system* is necessary for shifting visual attention in response to cues. It may be worth reconsidering the empirical support they offered for this thesis, in light of the apparently clear-cut findings of this article. Posner et al. required subjects to perform a simple visual-detection task either as a single task or while shadowing some spoken prose. The visual-detection task was preceded by cues that were valid most of the time. In the single-task condition, the usual cuing benefit was found: faster responses to the probes that were validly cued compared with invalidly cued probes. When the subjects concurrently shadowed, however, the cuing effect was apparently eliminated in one of four conditions examined: left visual field presentations and a 100-ms cue-stimulus interval. The cuing effect was intact despite the concurrent shadowing when the cue-stimulus interval was 800 ms or the cue was presented in the right visual field. Posner et al. concluded that the right anterior attention system is necessary for shifting of visual attention and that with this system occupied, shifts are delayed.

How are these results to be related to the present findings? It seems plausible that shadowing would at least intermittently occupy the response-selection mechanism, and thus it may be reasonable to equate Posner et al.'s anterior attention system with the hypothetical source of response-selection queuing. It seems likely, however, that shadowing would not constantly occupy this mechanism, given the possibility that substantial amounts of material might be buffered at both input and output. As Broadbent (1982) points out, such buffering may be responsible for cases in which shadowing seems to leave concurrent task performance unaffected (e.g., Airport, Antonis, & Reynolds, 1972). Why, then, do the conclusions of Posner et al. not jibe with the present findings? There are several major differences. One is that shadowing ties up some

mechanisms in addition to the source of response-selection queuing. Second, note that the cues in Posner's (1989) task are not logically necessary for performance of the detection task, whereas in the present experiments, performance would drop to the chance rate of 25% correct if the cues were not used. This raises the possibility that when a secondary-task manipulation reduces cuing effects in Posner et al.'s paradigm, it may not be because the manipulation makes it impossible for cue-induced attention shifts to take place but rather because it somehow reduces the incentives for the subject to perform these shifts. There are also some less plausible accounts for the difference between the Posner et al. conclusion and the current results. First, there is some dispute in the literature regarding the causes of cue-induced changes in simple detection RTs. They may partly stem from alterations in decision criteria (Shaw, 1984) rather than changes in sensitivity, and thus it is possible that the mechanisms responsible for the cuing effects studied by Posner et al. are different from those underlying the effects studied here. If a criterion-setting mechanism were responsible for cue-induced reductions in simple RT, and a different mechanism permitted selected items in a multi-item array to be remembered and reported, then the latter mechanism would seem to have the stronger claim to be referred to as *visual selective attention.* Finally, because the Posner et al. result is an unexpected interaction that involves cue-stimulus interval and hemifield and is significant at the .05 level, it even seems conceivable that it might be a statistical anomaly. Obviously, each of the possibilities mentioned could be evaluated by using various designs intermediate between those used here and those used in the studies of Posner et al. For present purposes, though I contend that although the difference is somewhat puzzling, nonetheless the Posner et al. data should not prevent us from reaching the conclusion the data reported in this *article* point *toward:* that a first task which causes dramatic postponement of second-task response selection does essentially nothing to delay second-task visual attention shifts.

It was also mentioned in the introduction that some patients with brain damage present a pattern of attentional neglect that affects both shifts of visual attention on the one hand and production of responses oriented to particular regions of space on the other. Rizzollati and Camarda (1987) suggested that visual selective attention is controlled by a circuit that is also involved in what has been termed *response selection* in this article. The data reported by Rizzollati and Camarda, however, entirely depend on the logic of associations rather than the logic of dissociations. That is, it hinges on the fact that certain symptoms are usually found together in patients or monkeys with focal lesions. As has often been pointed out (e.g., Coltheart, 1985), the tendency for two symptoms to be associated is not clear-cut evidence that the mechanisms underlying them are identical. For instance, if the neural substrates for two different functions are anatomically intertwined but functionally distinct, then damage to one will be associated with damage to the other. When careful behavioral analysis points to the functional independence of two mental operations but neuropsychological evidence suggests that they are generally associated, it seems most sensible to follow the behavioral evidence. (Note that this discussion actually over-

simplifies matters because there are really two logically distinct notions of functional independence at issue here: operating simultaneously and having a common neural substrate. Further discussion of these points would lead far afield, however.)

In fact, there is other evidence concerning neural bases that seems to be wholly consistent with the independence indicated by the present results. For instance, on the basis of single-unit response studies in the macaque, Goldberg and Segraves (1987) suggested that prefrontal cortical areas select motor responses from among multiple activated candidate actions in parallel with and independently from the more posterior visual-orienting system. Similarly, Shallice (1988) proposed that the frontal lobes contain a system devoted to scheduling and selection of motor actions that is quite independent of visual orienting. In fact, it is interesting to note that the range of activities currently associated with the processing bottleneck of simple dual-task situations seems to fit quite well with the functions generally attributed to the frontal lobes (including that subset of types of sacadic eye movements that are subject to dual-task interference; see Pashler et al., 1990). Unfortunately, though, there does not currently seem to be any definitive way of analyzing the neural basis of dual-task scheduling and conflict in detail, to test such conjectures. Therefore, for the moment, analysis of these fundamental questions must rely on behavioral experimentation. The present work and the studies that preceded it suggest that rich empirical constraints on theories can be obtained by using multiple and converging response measures, to examine interactions between tasks on a trial-by-trial basis.

Finally, the results described here also have obvious relevance to human performance in complex real-world tasks, such as aviation or driving. In such activities, it may be fortunate (but probably not fortuitous) that the selective uptake of information from the visual environment can operate simultaneously with the selection of motor responses. For example, consider a driver who is selecting an action like switching the radio dial or pressing the accelerator at the very moment a new visual input signals approaching pedestrians or vehicles. The peripheral cue (e.g., looming or motion) may be transitory, whereas the danger it signals will grow more critical with succeeding milliseconds. It would be troublesome, to say the least, if shifts in visual attention toward such peripheral events had to wait for time-consuming cognitive processes involved with selecting and planning the motor action. This raises the amusing possibility that although elaborate experiments and analyses were used to demonstrate the independence of visual attention shifts and motor-response selection, if this independence did not exist, common activities like driving, aviation, and many kinds of athletic performance might be impossible for humans to carry out as they do! Of course, to determine whether this is so one would need quite different sorts of research from that reported here— research in which subjects' performance in complex naturalistic activities was directly observed.

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