THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 1993, *46A* (1) 51-82

Saccadic Eye Movements and Dual-task Interference

Harold Pashler and Mark Carrier
University of California, San Diego, U.S.A.

James Hoffman
University of Delaware, U.S.A.

Four dual-task experiments required a speeded manual choice response to a tone in a close temporal proximity to a saccadic eye movement task. In Experiment 1, subjects made a saccade towards a single transient; in Experiment 2, a red and a green colour patch were presented to left and right, and the saccade was to which ever patch was the pre-specified target colour. There was some slowing of the eye movement, but neither task combination showed typical dual-task interference (the "psychological refractory effect"). However, more interference was observed when the direction of the saccade depended on whether a *central* colour patch was red or green, or when the saccade was directed towards the numerically higher of two large digits presented to the left and the right. Experiment 5 examined a vocal second task, for comparison. The findings might reflect the fact that eye movements can be directed by two separate brain systems—the superior colliculus and the frontal eye fields; commands from the latter but not the former may be delayed by simultaneous unrelated sensorimotor tasks.

Human beings sometimes experience great difficulty when they try to do more than one task simultaneously. This interference between tasks is intuitively obvious to everyone when the tasks are difficult, but it can be observed with even seemingly trivial sensorimotor tasks studied in the

---

Requests for reprints should be sent to H. Pashler, Department of Psychology 0109, University of California, San Diego, La Jolla, CA, 92093.

This work was supported by NASA Ames Research Center under Interchanges NCA2-225 and NCA2-414 with H. Pashler, by NIMH under Grant 1-R29-MH45584-01 to H. Pashler, and by the US Army Research Office under Contract DAAL03-86-0080 to J. Hoffman. The authors are grateful to Alann Lopes for outstanding technical assistance on all aspects of this project, to Ann Moses for help in running subjects, and to Alan Allport, John Duncan, Robert McCann, and Robert Rafal for useful comments on an earlier version.

laboratory. Research on dual-task performance seeks to understand the fundamental causes of this interference. This understanding should help provide insight into the functional organization of the brain. In addition, it should provide practical information for designing complex systems requiring rapid responses from human operators, in fields such as aviation. One approach to determining the causes of dual-task interference is to determine under exactly what circumstances particular types of interference do and do not arise.

This article examines a behaviour of substantial practical and theoretical interest, namely saccadic eye movements elicited by various different forms of stimuli under various kinds of instructions. There has been very little research on saccadic eye movements performed in a dual-task situation, and the results of the studies that have been performed are quite inconclusive. The work reported here demonstrates that saccades sometimes seem to be exempt from the most severe dual-task interference that has been repeatedly observed with tasks involving manual, vocal, and foot responses. In the General Discussion, we raise the possibility that this relative lack of interference between saccades and concurrent tasks may be related to the existence of two different neural systems for eye movement control, as revealed by recent physiological studies.

Dual-Task Interference

Interference between tasks has been examined in many different laboratory tasks. Many studies have paired complicated tasks that require several seconds or even minutes to complete, observing overall performance tradeoffs between the tasks (e.g. tracking a visual stimulus and shadowing spoken input). Such tasks can only be analysed in a rather coarse way (e.g. aggregating performance errors over many seconds), and this cannot reveal much about the underlying causes of dual-task interference. The alternative is to examine pairs of very simple and brief tasks, with trial-by-trial analyses of the distribution of latencies on each task. This approach was begun by researchers (notably A.T. Welford, 1952) in studies of the so-called psychological refractory period experiment (henceforth, *PRP*). Here, two stimuli (57 and 52) each require a separate response (*R1* and *R2*, respectively), and the reaction time from each stimulus to the corresponding response is observed. The design allows one to examine how the latency of each response is affected by temporal overlap between the tasks (manipulated by varying the stimulus onset asynchrony from S1 to S2, or *SOA*), and also to examine dependencies between the latencies on the two tasks. In studies that have employed this method, the general finding is that the second response is delayed as the SOA is reduced (the *PRP effect*). This delay suggests that performing one task makes some limited capacity mechanism or resource unavailable for the other task during the period of temporal overlap.[1]

Recent studies have provided converging evidence for the idea that the most fundamental cause of interference in the PRP paradigm is postponement of the stage of response selection in the second task, and possibly also "decision-making" in some general sense (see Pashler, 1992, for a review). The most natural account of this postponement (which was first suggested by Welford) is that a single "bottleneck" mechanism carries out response selection in any task, and when it is occupied with one task, it cannot carry out the corresponding work in another task.

Evidence for the response selection bottleneck hypothesis comes from several different kinds of experiment. In one, S2 is manipulated to vary the duration of particular target stages in Task 2. (For example, the intensity of a visual S2 can be reduced, to prolong perceptual processing in Task 2.) The response selection postponement hypothesis makes very specific predictions for the joint effects of SOA and these S2 difficulty factors. When the factors prolong stages prior to response selection, underadditive interactions with SOA are predicted. When the factors prolong response selection itself or subsequent stages, the factor should have effects that are additive with the slowing caused by reduced SOA. These predictions have been confirmed experimentally using various different pairs of choice reaction time tasks (Pashler, 1984; Pashler & Johnston, 1989; McCann & Johnston, 1992; Fagot & Pashler, in press). In addition, the response selection postponement account correctly predicts the existence of strong positive dependencies between the first and second task latencies, as well as some fine-grained aspects of these dependencies as they vary with SOA (Pashler, 1989).

Another source of evidence for the response selection postponement analysis comes from experiments where a speeded first task is combined with a second perceptual judgement task (with a brief masked visual display and an unspeeded response). The response selection postponement hypothesis claims that perceptual processing on the second task is *not* delayed by processing on the first task; therefore, the accuracy of second-task perceptual judgements should not be affected as the SOA is reduced (over the range from completely non-overlapping to near-simultaneous performance). Indeed, there is very little interference, when the first task is perceptually easy and S1 and S2 are in different modalities (Pashler, 1989). Furthermore, the speed of the first task and the accuracy of the second task show no meaningful dependencies.

---

[1] The notion of a bottleneck mechanism need not entail that the processing occurs at a single neural site. It would be functionally equivalent if there were a set of processes each carried out by different neural machinery, if this machinery was interconnected so that when one process on the set was active, the others were inhibited.

When both tasks require difficult perceptual discriminations in the same modality, on the other hand, an additional type of interference can arise (Kleiss & Lane, 1986). This component seems to be independent of response selection postponement (Pashler, 1989), ruling out the possibility that there is a "central processor" responsible both for response selection and for the more difficult perceptual processing.

Generality Across Tasks

In summary, competition for a central mechanism that carries out certain decisions and selects actions seems to be the most basic cause of interference observed between simple tasks. If it is selection and not execution of the response that is a bottleneck, the choice of particular response modalities in the two tasks should not matter. There has been quite a bit of controversy on this point. In some cases, there seemed to be little interference when one task was manual and one task was vocal response (McLeod, 1977a). This issue was examined by Pashler (1990), who compared vocal-manual response combinations with manual-manual combinations. In the PRP paradigm, there was clear interference observed with both response combinations, with only slightly more interference for the manual-manual combination. However, when the PRP task was modified so that the order of stimulus onset was unpredictable to the subject (as it had been in McLeod's 1977 study), then the manual-manual combination showed much more interference than did the manual-vocal combination. It seems that this previously unsuspected interaction between order of stimuli and response modality had overshadowed the basic dual-task interference and led to the mistaken impression that manual-vocal combinations show no interference. We have also observed typical PRP effects when a choice response made with the foot is combined with a vocal response or with a manual response (Pashler & Christian, 1991) and with various other manual-vocal combinations (Pashler, 1989).

Eye Movements and Dual-task Interference

People make eye movements almost continuously, but they have been almost completely neglected in dual-task research. The omission is striking, because in ordinary life eye movements are essential for a wide range of human activities. In addition, eye movements have special and interesting connections to visual attention (Kowler & Zingale, 1985; Shepherd, Findlay, & Hockey, 1986). People are rarely conscious of devoting much conscious mental activity towards the goal of moving the eyes per se, and thus one does not normally think of a task like reading or driving as a dual-task situation, just because it involves making eye movements. This makes especially intriguing the question of whether the central response selection mechanism is invoked each time an eye movement is produced.

Most of the published studies that have examined eye movements together with other concurrent motor actions have looked at eye movements combined with (manual) pointing responses. Several investigators had subjects make eye movements and hand movements towards the same target (Mather & Putchat, 1983; Mather & Fisk, 1985; Megaw & Armstrong, 1973). Neither movement was delayed very much compared to single-task performance (at least by comparison to typical PRP effects).

It might seem that this fact by itself refutes any central bottleneck model as applied to oculomotor behaviour: if response selection operated on only one task at a time, then substantial delays might be expected when subjects must simultaneously look and point. However, in these experiments the subjects were pointing and looking to the *same* target. For this reason, the two actions might be selected (and, up to some point, produced) as a single response. Fagot and Pashler (in press) required subjects to make both manual and vocal choice responses to the colour of a single stimulus. Little slowing of either response was observed compared to single-task controls, and a variety of converging experiments indicated that subjects selected a vocal-manual response couplet as if it were a single response; for example, manipulations that delayed one response selection but not the other in single-task conditions "carried the other response along" in the dual-task condition. It appeared, then, that the absence of interference reflected the fact that only one response selection was occurring. The fact that there are no bottleneck effects in the selection of a single response couplet is no argument against the existence of a bottleneck when two independent response selections are required. Thus, the fact that hand and eye movements to the same target show little interference does not rule out the possibility that control of eye movements depends on the same bottleneck mechanism revealed in studies with hand, foot, and mouth responses.

For this reason, then, if one wants to investigate dual-task interference in generating saccadic eye movements, one must combine an eye movement task with another task that is logically independent of the eye movement. One study that meets this requirement was reported by Malmstrom, Reed, and Weber (1983), who had subjects perform repetitive oscillatory step-jumping saccades with or without a concurrent task. The concurrent task was a go/no-go task with an auditory stimulus and a manual response. Malmstrom et al. recorded the accuracy of saccadic responses as well as performance on the auditory-manual task. They found that the saccadic task suffered some interference from the concurrent auditory-manual task. As latencies were not observed for both tasks, however, this does not show that postponement occurred. It is possible, for example, that the auditory-manual task may have disrupted advance preparation of the mental set governing the eye movement, rather than selection of individual eye movements (Gottsdanker, 1980; Pashler, 1984). In addition, the eye movement task used by Malmstrom et al. did not require choice and therefore could potentially bypass response selection.

Current Studies

The purpose of the present studies was to determine whether saccadic eye movements are subject to dual-task interference, using a PRP task that allows a detailed trial-by-trial analysis of performance. For this purpose, two discrete choice tasks were used on every trial: (1) a two-choice reaction time task with an auditory stimulus and a manual response, and (2) a saccadic eye movement task with visual stimuli and instructions that varied from experiment to experiment. In each case, the two tasks were independent, and neither response could be predicted prior to the appearance of the corresponding stimulus. The SOA between the two stimuli was varied systematically. The first experiment began with the very simplest form of saccadic task, and the subsequent experiments added progressive complications to the process of selecting the destination for the eye movement. In almost all of the studies of the PRP effect cited above, the order of stimuli was fixed (i.e. all the SOAs have been positive). However, in the studies reported here, negative SOAs were also included because the latency for eye movements is comparatively short; therefore, negative SOAs might be required to reveal any possible interference. We begin with a general description of the method, to avoid redundancy.

GENERAL METHOD

Subjects. Undergraduates at the University of California, San Diego, participated as subjects in the experiment, either in partial fulfilment of a course requirement or in return for payment. A large number of subjects participated in the first few experiments but did not produce analysable data because of various problems with the eye movement recording apparatus.

Apparatus and Stimuli. The experiments were controlled by IBM PC microcomputers. Visual stimuli were presented on either Princeton Graphics SR-12 monitors, or NEC Multisync II monitors. Stimulus S1 was a tone, at 300 or 1000 Hz, lasting for 200 msec. The S2 stimulus for the eye movement (henceforth, *visual target)* varied from experiment to experiment. The visual stimuli were presented against a black background. (The refresh cycle of the monitors means that individual RTs and SOAs were subject to an uncertainty of up to 16 msec, which is not consequential for our purposes.)

Subjects' eye movements were recorded using electrooculographic recording (EOG) horizontal channel only. Two Tronomed electrodes were applied to the subjects' left and right temples, and one to the forehead. The signals were filtered with a Coulbourn Model 575-42 EOG/ENG Bandpass Biofilter and amplified on a Coulbourn Model 575-07 Bioamplifier. The data were digitized with a DTC Model DT2801 A/D converter, which transferred the data to the PC. Saccadic eye movements were detected using an algorithm that sampled this digitized eye position signal at 200 Hz. The algorithm was based on the suggestions of Oster and Stern (1980) and basically detected slope changes in the eye position signal. The computer saved both the latency and direction of saccades detected on a given trial.

Design. The experiments were divided into 12 blocks of 35 trials per block. There were 7 different SOAs (measured from onset of the tone to onset of the visual target—thus, when the SO A is negative, the visual target preceded the tone): -150, -50, 50, 150, 250, 500, and 750 msec. There were 5 trials at each SOA in each block, and all trials in a given block were presented in random order. The direction to which the subject was required to saccade was chosen at random with replacement.

Procedure. The subjects were given written instructions describing the tasks. The instructions stated that the subjects should respond as quickly as possible with his or her right hand to the pitch of the tone, and "glance" as quickly as possible directly towards the visual target, which was defined differently in each experiment. Nothing was said about order of stimuli or order of responding. Each trial began with a fixation point—a plus sign that was presented in the centre of the screen. The subject was instructed to fixate this point at the onset of each trial, and the fixation point remained present throughout the trial; 1500 msec after its onset, the first of two stimuli requiring responses was presented (at positive SOAs, this was the tone; at negative SOAs, this was the visual target or targets). The visual target(s) remained on the screen for approximately 2000 msec. The correct response to a low or high tone was to press the full stop or semicolon key with the index or middle finger of the right hand, respectively. The interval between the offset of the visual target(s) on one trial and the appearance of the fixation point for the next trial was in the range from 0.5 to 2.0 sec (it varied depending on the amount of computation required to detect the saccade). Subjects were not presented with feedback of any sort. At the end of each block, subjects rested until they felt like resuming. There was a break after the first six blocks of trials, during which time the EOG equipment was recalibrated. This break lasted between 5 and 10 min. The latency of the button-push response was computed from the onset of the tones.

EXPERIMENT 1 Saccade to Single Target

In the first experiment, subjects attempted to perform two temporally overlapping tasks. One task was a two-alternative manual button push response to a high- or low-pitch tone. The other task simply consisted of making a saccadic eye movement towards a single visual stimulus that appeared to the left or right of the centre of the computer display. The position of the stimulus was not known in advance. The tone is designated S1 and the visual stimulus S2, for the purpose of determining the SOA, despite the fact that the stimulus order was reversed for the negative SOAs. The SOA was varied over the range from -150 msec to +750 msec. The long SOAs are more appropriate than a single-task condition as a baseline for examining performance in each task without interference from the other task, because the need to *prepare* both tasks is preserved (for a discussion of this issue see Gottsdanker, 1980; Pashler, 1984; 1989).

Method

Valid data were obtained from eight subjects in this experiment. The visual target was a plus sign. It was presented either directly to the right or directly to the left of and 10.3 cm from the centre of the screen (this distance corresponded to approximately 9.7° visual angle, based on a typical viewing distance of about 60 cm). The visual target measured 1 cm x 1 cm (0.95° x 0.95°). The instructions stated that the subject should respond as quickly as possible to the pitch of the tone and simply "glance" as quickly as possible directly towards the visual target as soon as it appeared.

Results and Discussion

Figure 1 presents the mean reaction times for button-push responses to the tone and for saccade responses to the visual target, as a function of SOA. The manual and saccade responses were subjected to separate analyses of variance. The manual response latencies show a general upward trend with SOA, increasing from 455 msec at the -150 SOA to 546 msec at the +750 SOA; this SOA effect is significant, $F(6, 42) = 10.8$, $p < 0.001$. The eye movement response latencies gradually decrease with SOA, from 328 msec at -150 msec to 195 msec at +750 msec; the effect is significant, $F(6, 42) = 55.6$, $p < 0.001$. The error rate on the manual response was 9.6%, 8.4%, 4.0%, 5.4%, 3.2%, 3.6%, and 1.8% for the different SOAs (in increasing order).

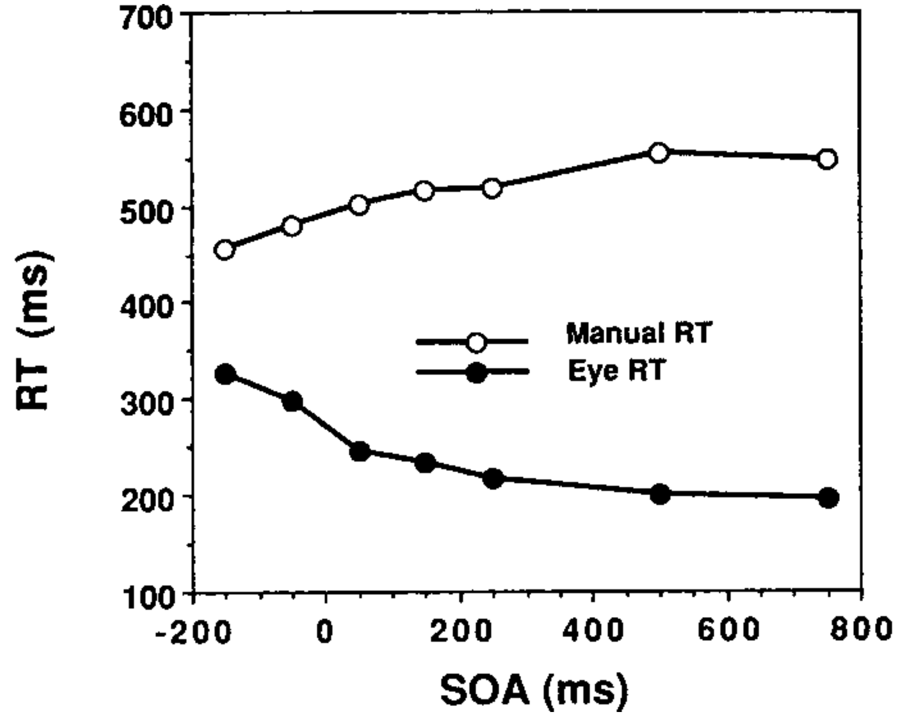


FIG. 1. Mean eye movement and manual RTs as a function of SOA—Experiment 1.

On superficial examination, the statistically significant upward progression in eye movement RTs as SOA is shortened looks vaguely like a PRP function. However, a closer examination reveals that it is quite different. Consider first the changes that occur as the SOA is reduced from 750 to 50 msec. There is a rather modest increase in eye movement latencies, from 194 to 245 msec. At the 750-msec SOA, the mean eye movement response actually occurs 398 msec later in time than the mean manual response (750 + 194 - 546). On the other hand, at the 50-msec SOA the mean eye movement response is actually 205 msec *earlier* in time than the mean manual response (50 + 245 - 500). Plainly, then, if there were response selection postponement operating, this should have been manifested in changes occurring over this range of SOA variation. Yet the variation is modest in the eye movement RTs (and negligible in the manual RTs).

Next, note that as the SOA is reduced further from 50 to -150 msec, a more marked increase in eye movement latency occurs, from 245 to 328 msec. Over this entire range, the eye movement is, on average, *preceding* the manual response by a substantial amount of time. Thus, postponement on the typical trial cannot be responsible for delays in the eye movement—the response that is produced first. But the manual RTs are actually *decreasing* over this range, so these—typically the second responses produced—cannot be subject to postponement either.

In short, the eye movements are significantly slowed as the SOA is reduced, but the magnitude of this increase is modest, and its pattern does not suggest postponement. Further analyses explore these differences in greater detail, examining them side by side with the data from the other experiments.

EXPERIMENT 2
Saccade towards Colour Target

The second experiment was similar to the first, except that the saccadic eye movement task required a discrimination based on colour: a red and a green patch appeared on the screen, one to the left and one to the right of centre, and the subject looked towards the patch with the specified target colour (which was different for different subjects, but remained constant throughout the experiment). There is little doubt that colour discrimination is not prevented by response selection in a concurrent task (for example, Pashler, 1989, found little interference with the perceptual aspects of colour-form conjunction search). In addition, there was a control condition with no first task; the same tones and colour patches were presented, and subjects made eye movements to the target patch, but they did not respond in any way to the tones.

Method

Eight undergraduates at the University of California, San Diego, provided usable data in the main experiment, and four subjects served in the control experiment. On each trial, the stimulus for the eye movement consisted of two rectangular coloured patches. The patches measured 1.8 cm wide by 0.7 cm high (1.7° x 0.7°); one was red and one was green. In each display, one patch was located 10.3 cm (9.7°) to the left of the centre of the screen, and the other patch was located 10.3 cm to the right. It was randomly determined which colour would be on which side. Half of the subjects were instructed always to look towards the red patch, and half towards the green. The subject was instructed always to look towards the patch of the particular target colour, and both colour patches appeared on the screen at the same time. Subjects in the control condition did not make any manual responses to the tones, although the tones were still presented.

Results and Discussion

Figure 2 presents the mean reaction times for button-push responses to the tone and for saccade responses to the visual target, as a function of SOA, for both the experimental and no-first-task control conditions. The manual and saccade responses were subjected to separate analyses of vari-

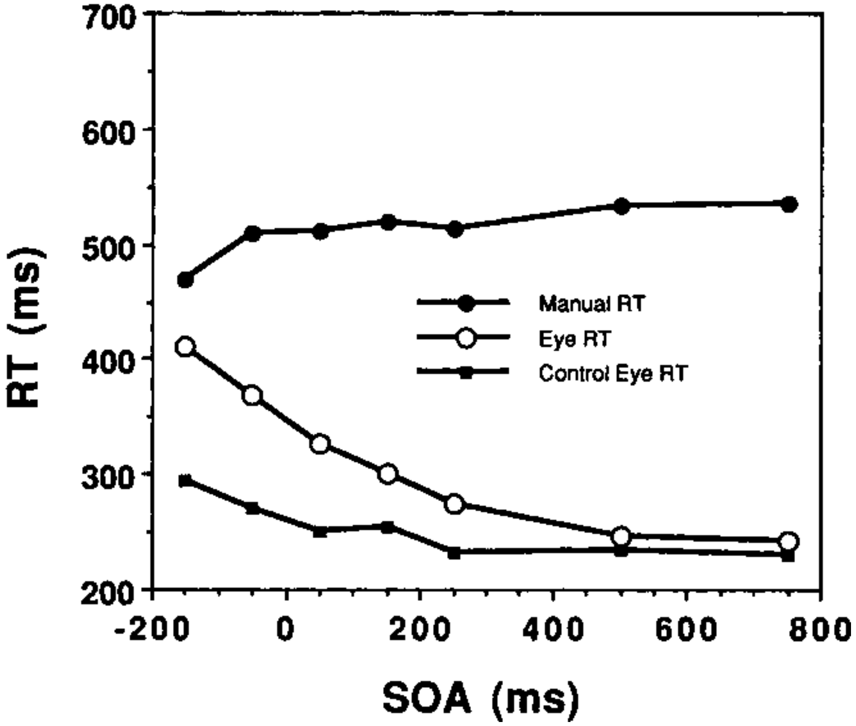


FIG. 2. Mean eye movement and manual RTs as a function of SOA—Experiment 2.

ance. For the experimental group, the manual response latencies show a general upward trend with SOA, increasing from 468 msec at the -150 SOA to 535 msec at the +750 SOA; this SOA effect is significant, *F*(6, 42) = 6.7, $p < 0.001$. The eye-movement response latencies gradually decrease with SOA, from 411 msec at -150 msec to 241 msec at +750 msec; the effect is significant, *F*(6, 42) = 31.8, $p < 0.001$. For the control group, the RTs also decreased with SOA, ranging from 294 msec at the -150 SOA to 231 msec at the +750 SOA; the effect was significant, *F*(6, 18) = 6.1, p < 0.001. The error rates on the manual response were 11.3%, 6.4%, 3.8%, 3.3%, 3.1%, 2.4%, and 1.0% as SOA ranged from -150 to +750; this effect was significant, *F*(6, 42) = 6.9, $p < 0.001$.

The eye-movement latencies are appreciably longer in this experiment than in the preceding experiment. Nonetheless, the basic effects appear extremely similar. They can be summed up as a slowing in the eye-movement response at shorter SOAs, but seemingly much less than a full-blown PRP effect. The data will be examined in greater detail below. The results of the control experiment show that some eye movement slowing with SOA seems unrelated to performing the first task. Presumably, this reflects the effects of temporal uncertainty, i.e. the longer the SOA, the more assurance the subject will have about when the stimulus will arrive. It is interesting that this seems to produce a much larger effect than we observed with a manual classification task (Pashler & Johnston, 1989), where a similar control condition showed little in the way of an SOA effect. Larger effects have been previously observed with simple RT as the second task, however (Davis, 1959).

EXPERIMENT 3

Central Colour Cue

In the third experiment, the subject was required to look either right or left on the basis of the same red vs. green colour discrimination as the one employed in the second experiment. However, in this experiment the signal for the eye movement was a *central* colour patch, and depending upon its colour, the subject looked either left or right. Two identical eye-movement targets (plus signs) were presented in advance, one to the left and one to the right of fixation; these marked the potential targets for the eye movement. Thus, this experiment required the same sensory discrimination as Experiment 2, but it also required a response selection for the eye movement that depends upon looking up an arbitrary connection in memory (namely, the association between colour and direction).

Method

Eight undergraduates at the University of California, San Diego, provided data. On each trial, the stimulus for the eye movement consisted of a rectangular coloured patch in the centre (1.7° x 0.7°), together with a pair of plus signs located 9.7° to the right and left of the centre of the screen. The colour of the central patch was chosen at random. Half of the subjects were instructed to look at the left eye movement target if the colour patch was red, and at the right target if the patch was green; the assignment was reversed for the other half of the subjects. When the trial began, three plus signs appeared (the central fixation, plus the left and right eye-movement targets). When the visual stimulus for the eye movement was presented, the central warning fixation was replaced with the colour patch, but the two peripheral eye movement targets remained present. The latency of the eye movement was computed from the onset of the central colour patch.

Results and Discussion

Figure 3 presents the mean reaction times for button-push responses to the tone and for saccade responses to the visual target, as a function of SOA. The manual and saccade responses were subjected to separate analyses of variance. The manual response latencies show a gradual upward

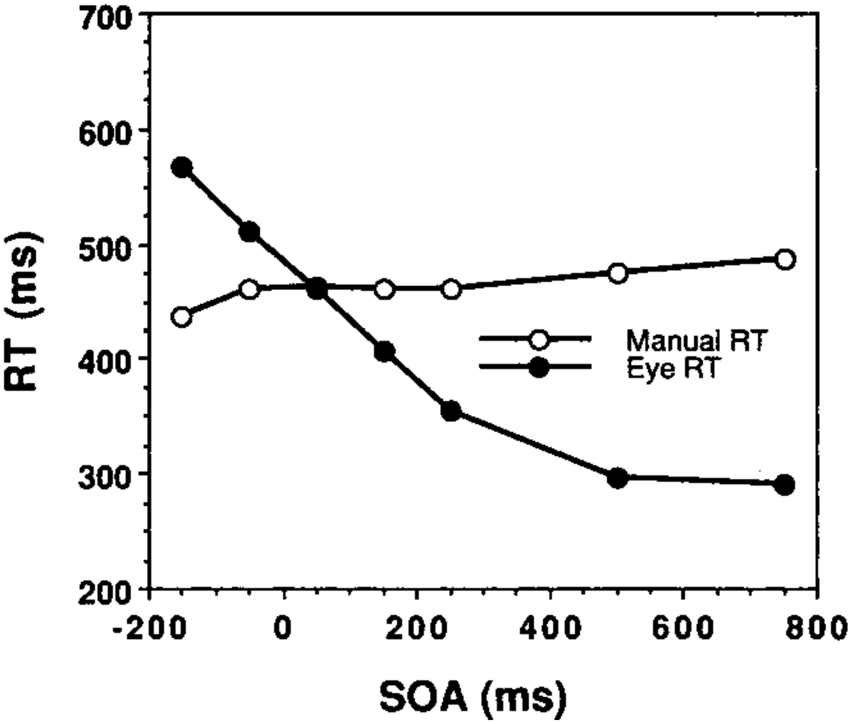


FIG. 3. Mean eye movement and manual RTs as a function of SOA—Experiment 3.

trend with SOA increasing from 437 msec at the -150 SOA to 488 msec at the +750 SOA; this SOA effect is significant, $F(6, 42) = 6.0$, $p < 0.001$. The eye movement response latencies decrease markedly with SOA, from 567 msec at -150 msec to 290 msec at +750 msec; the effect is significant, $F(6, 42) = 125.4$, $p < 0.001$. The manual error rates basically decreased with SOA: 8.9%, 4.4%, 4.0%, 3.0%, 2.75%, 1.1%, and 1.5%, $F(6, 42) = 8.1$, $p < 0.001$.

Compared to the previous experiments, the eye movement responses here show a more marked increase as the SOA is reduced. This appears to be more in line with what one would expect for a PRP effect. More detailed analyses will be reported below to explore the question of whether there really is a discontinuity between the results of this experiment and those of the first two experiments.

EXPERIMENT 4
Saccade to Highest Digit

The fourth experiment added a complex stimulus discrimination. Two large digits were presented to the left and right of the fixation point; the digits were large enough that the subject could read both while still looking at the central fixation point. The subject was instructed to move his or her eyes to look directly at the numerically higher digit. This experiment was essentially like Experiment 2, except that the direction of the eye movement was determined by a symbolic attribute of the two stimuli, rather than a simple physical feature.

Method

Eight undergraduates at the University of California, San Diego, provided usable data. On each trial, two digits were presented to the left and right of the fixation point (at a distance of 10 cm, or 9.5°). Each digit measured 3.1 cm high by 1.2 cm wide (2.96° x 1.15°). The highest digit was selected randomly from the range 3 through 9 (inclusive); the distractor digit was selected randomly from the range from one up to the highest digit minus one (inclusive). Subjects were instructed to look towards the highest digit.

Results and Discussion

Figure 4 presents the mean reaction times for button-push responses to the tone and for saccade responses to the visual target, as a function of SOA. The manual and saccade responses were subjected to separate analyses of variance. The manual response latencies show an upward trend with SOA, increasing from 519 msec at the -150 SOA to 548 msec at the +750 SOA; this SOA effect is not quite significant [*F*(6, 42) = 2.0,

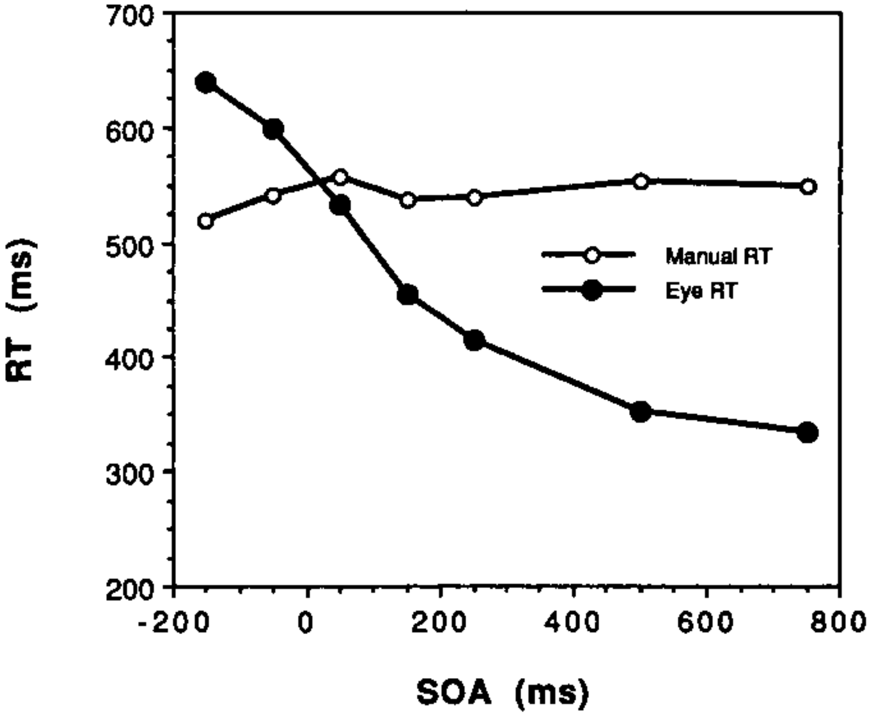


FIG. 4. Mean eye movement and manual RTs as a function of SOA—Experiment 4.

$0.05 < p < 0.10$]. The eye movement response latencies decrease markedly with SOA, from 640 msec at -150 msec to 335 msec at +750 msec; the effect is significant, $F(6, 42) = 23.3, p < 0.001$. The manual error rates were 7.3%, 5.78%, 3.3%, 4.3%, 2.5%, 0.8%, and 2.8% from shortest to longest SOA; the effect of SOA was significant, $F(6, 62) = 3.1$.

The results of this experiment are extremely similar to those of Experiment 3, which involved a central colour target rather than a peripheral symbolic target. In both situations, there was a substantial increase in the eye movement RT as the SOA was reduced, although one might reasonably ask whether the results differ qualitatively or merely quantitatively from those of the first two experiments.

EXPERIMENT 5
Vocal/Manual Control

The final experiment was a control task involving the same auditory-manual first task as the previous four experiments, but combining that with a visual-vocal, rather than visual-oculomotor task. There is really no single appropriate control condition, but the present task was designed to match the important features of Experiment 3 as much as possible. In Experiment 3, the eyes moved left or right, depending upon whether a central colour patch was red or green. In the present experiment, subjects said "left" or "right", depending upon whether a central colour patch was red or green. Intuitively, this seemed to match roughly the degree of arbitrariness of the S-R mapping in Experiment 3. (Note that there is no way to match the time taken for the motor response *execution,* however.)

Method

Eight undergraduates at the University of California, San Diego, participated as subjects. The subjects' vocal responses were timed (but not scored for accuracy), using the Gerbrandts' Model G1341T Voice-Activated Relay and the DAK industries "Audio-Telescope" directional microphone. Subjects were instructed to say "left" or "right" where they would have looked left or right in Experiment 3. The instructions explicitly discouraged subjects from "grouping" their responses. Equal numbers of subjects had each of the two possible assignments. There were 10 blocks of 42 trials, 6 per SOA condition.

Results and Discussion

Figure 5 presents the mean reaction times for button-push responses to the tone and for vocal responses to the visual target as a function of SOA. The manual and vocal responses were subjected to separate analyses of

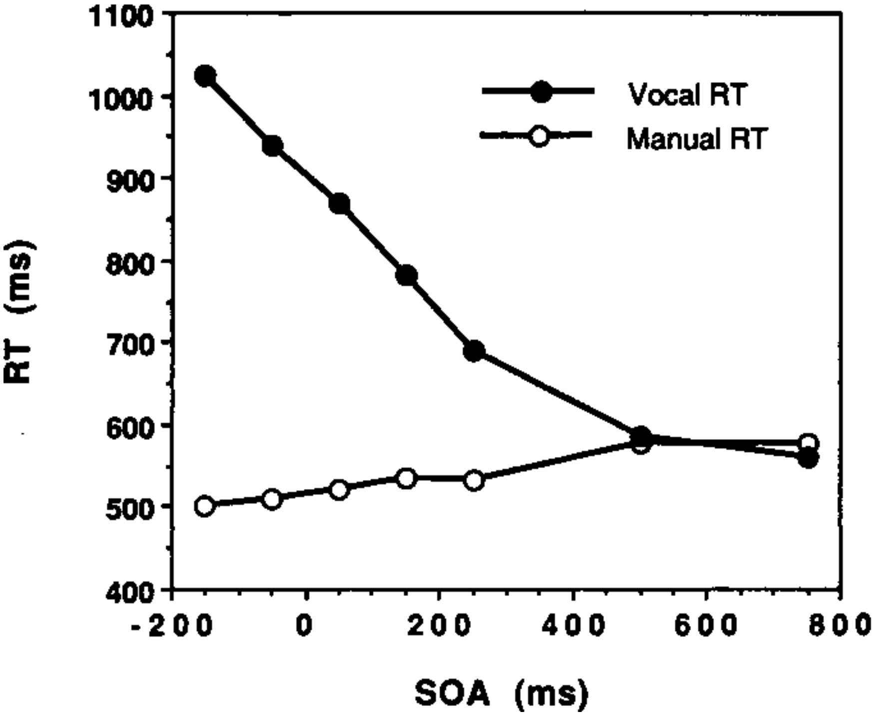


FIG. 5. Mean vocal and manual RTs as a function of SOA—Experiment 5.

variance. The manual response latencies show a gradual upward trend with SOA, increasing from 501 msec at the -150 SOA to 578 msec at the +750 SOA; this SOA effect is significant, *F*(6, 42) = 4.7, $p < 0.001$. The vocal response latencies decrease very dramatically with SOA, from 1024 msec at -150 msec to 561 msec at +750 msec; the effect is significant, *F*(6, 42) = 99.0, $p < 0.001$. The effect of SOA on manual error rates was significant, *F*(6, 42) = 5.1, $p < 0.002$. The manual errors were 8.6%, 6.8%, 5.1%, 3.5%, 4.0%, 1.5%, and 0.6% (from shortest to longest SOA). The results show an obvious PRP effect, with more increase in the second reaction times than was observed in the preceding experiments. First, note that the result adds strength to the conclusions of Pashler (1990), showing strong evidence of task postponement when tasks involving manual and vocal responses are combined (thus contradicting proposals of McLeod, 1977a, and others). The additional analyses compare performance in the five experiments in greater detail.

FURTHER RESULTS AND DISCUSSION
Experiments 1-5

The findings noted thus far can easily be summarized. When the task is to move the eye to the single spot (Experiment 1) or to the colour patch with a particular colour (Experiment 2), there is a very mild increase in eye movement RTs as temporal overlap is increased (i.e. as the SOA is reduced). Some portion of this is likely to be attributable merely to temporal uncertainty, as demonstrated by the control condition in Experiment 2. The increase in RT2 with SOA is greater in magnitude when the eye movement is triggered by a *central* colour discrimination (Experiment 3), or by a peripheral but symbolic discrimination (Experiment 4). Finally, a task that appears rather similar to that of Experiment 3 in terms of S-R compatibility but which has a vocal response substituted for the eye movement shows a more dramatic interference effect than any of the combinations involving oculomotor tasks.

Fortunately, given the PRP design employed here, we do not need to stop with an examination of mean RTs, as the bivariate RT distribution for each subject and SOA may reveal additional clues about what is going on.

Interresponse Interval Distributions

As noted above, the mean RTs suggest that as the SOA was reduced, the order of the eye movement and the manual response switched in the first two experiments. At the long positive SOAs, the eye movement occurred long after the manual response, whereas at the negative SOAs the eye movement appeared well before the manual response. By contrast, in Experiments 3 and 4 the increase in RTs for the eye movement as SOA was reduced was so great that stimuli were often responded to in the order they were presented, judging by the mean RTs. However, mean RTs may or may not be representative of the complete distribution. For example, if the order in which the two tasks were executed sometimes switches (with the second response being delayed), this might not be evident in the mean RTs. To look at the relative timing of the two responses in greater detail, we examined the distribution of interresponse intervals (IRIs) as a function of SOA for each of the experiments. To do this, the IRI was calculated for each correct trial (IRI = RT2 + SOA - RT1). Then, for each subject, for each SOA, the IRIs were ranked, and the 5th, 10th, . . ., 95th percentiles were determined in the standard way, and they were averaged across subjects. Figure 6, Panels A-E present the resulting Vincentized cumulative interresponse interval distribution with SOA as a parameter. The results are orderly and support the impression conveyed by the mean RTs. For the first two experiments, the distributions change little in shape, basically moving leftward as the SOA is reduced. At the shortest SOA (-150 msec), virtually the entire eye movement distribution precedes the manual response, and the median response precedes it by a substantial duration. If the two tasks were completely independent, the distributions shown in the figure should differ from each other only by a leftward shift, with the magnitude of the shift corresponding to the difference in SOA between it and the neighbouring distribution. The results for Experiments 1 and 2 are not too far from this pattern. The main deviation in the latter case is at the -150 and -50 msec SOAs. It is not clear what might be causing these deviations, but they are relatively modest.

When we turn to Panels C and D—the results of Experiments 3 and 4, where a refractory effect was more apparent—the results are quite different. Here there is an obvious bunching of the interresponse intervals around zero. Loosely speaking, one might say that the system "resists" producing the eye movement response much before the manual response. Finally, in the manual/vocal control (Panel E) there is a similar bunching up, but notice that here the bunching up actually occurs around an IRI of +350 msec, rather than zero.

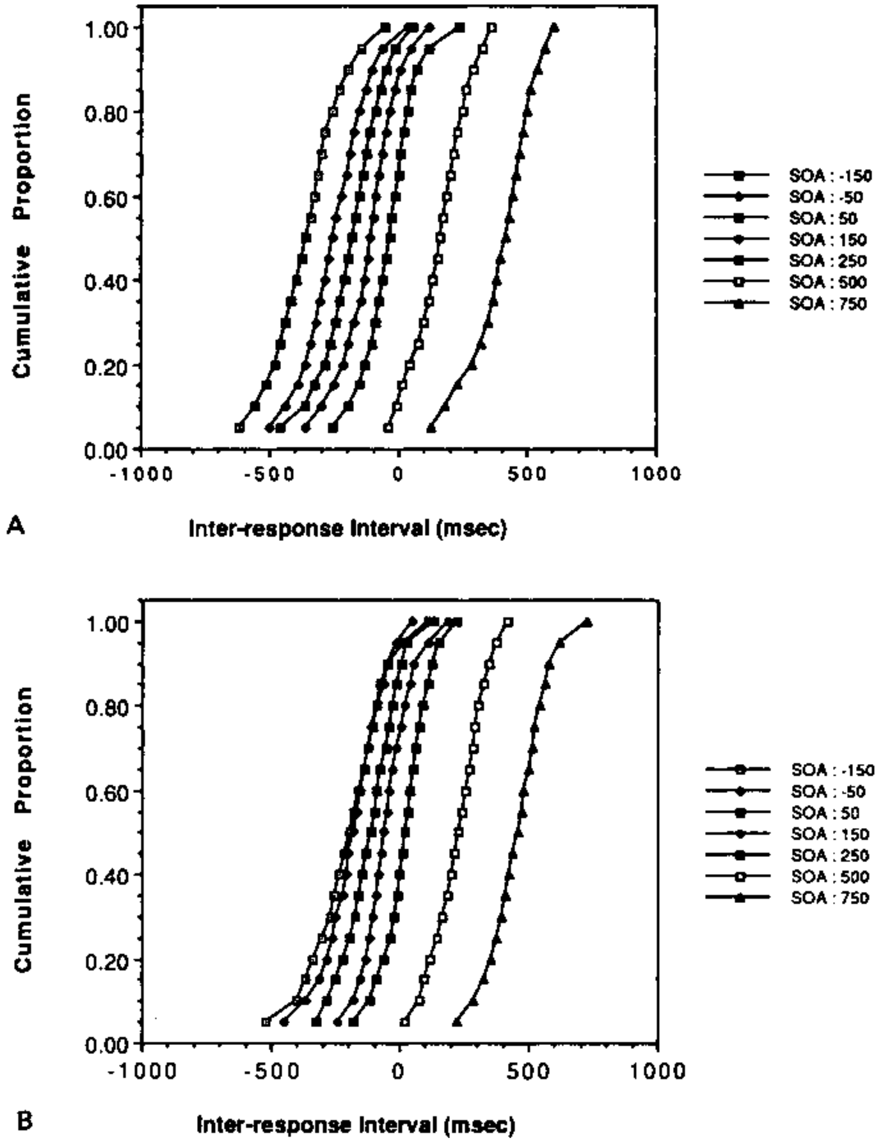
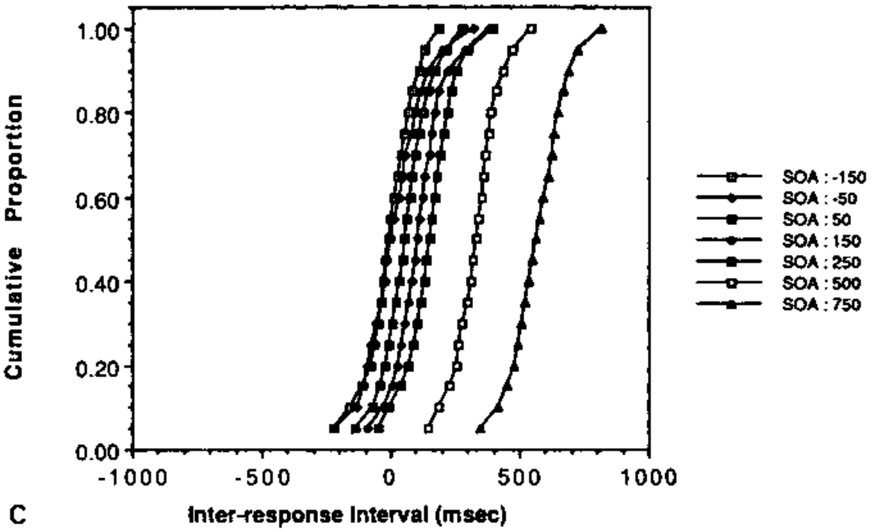
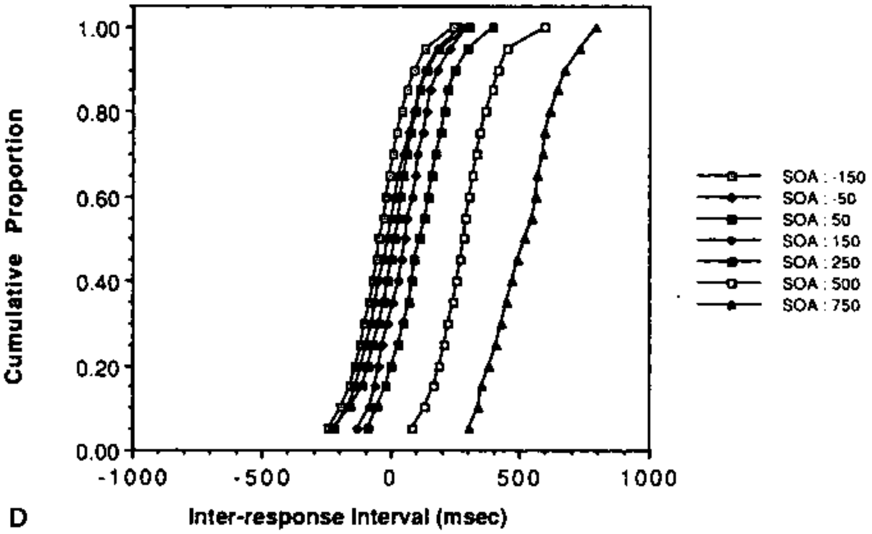


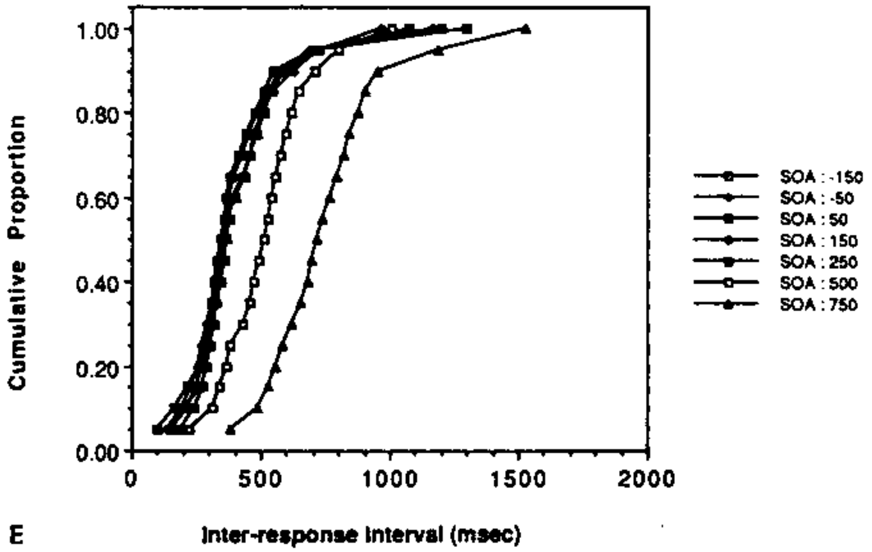
FIG. 6. Panels A-E: Vincentized distribution of interresponse intervals as a function of SOA, for Experiments 1-5, respectively.


Cumulative Proportion
1.00
0.80
0.60
0.40
0.20
0.00
-1000
-500
0
500
1000
Inter-response Interval (msec)
SOA : -150
SOA : -50
SOA : 50
SOA : 150
SOA : 250
SOA : 500
SOA : 750

C


Cumulative Proportion
1.00
0.80
0.60
0.40
0.20
0.00
-1000
-500
0
500
1000
Inter-response Interval (msec)
SOA : -150
SOA : -50
SOA : 50
SOA : 150
SOA : 250
SOA : 500
SOA : 750

D


Cumulative Proportion
1.00
0.80
0.60
0.40
0.20
0.00
0
500
1000
1500
2000
Inter-response Interval (msec)
SOA : -150
SOA : -50
SOA : 50
SOA : 150
SOA : 250
SOA : 500
SOA : 750

E

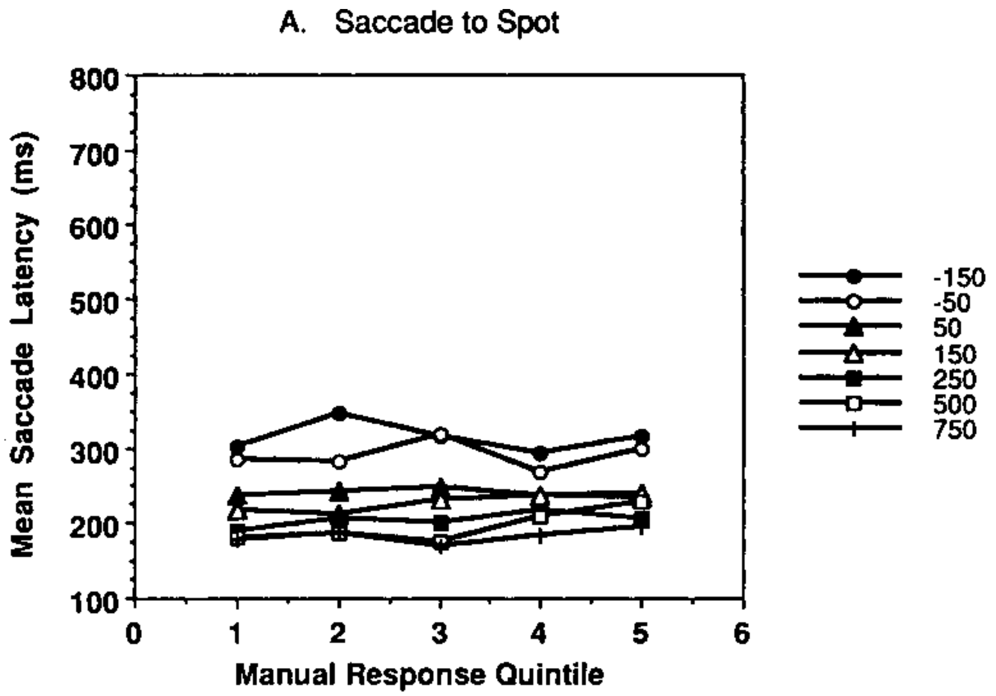
In sum, the Vincentized interresponse interval distributions reveal a pattern of individual R1 and R2 latencies that is broadly consistent with the impression conveyed by the means.

Interresponse Dependencies

Having confirmed that in Experiments 3 and 4 there is a clear tendency for something to prevent the interresponse intervals from falling much below zero, we now turn to the question of how the speed of the eye movement and the speed of the manual response covary from trial to trial. The IRI distribution by itself cannot answer this question. Obviously, if critical stages in one task wait for critical stages in another, there should be a clear dependency between RT1 and RT2, with slower responses on one task associated with slower responses on the other. This dependency should increase as the SOA is reduced. Indeed, this has been observed with tasks involving two manual responses, and also tasks requiring manual, vocal, and foot responses (Pashler, 1989, 1990, 1991; Fagot & Pashler, in press; Pashler & Christian, 1991). Following the earlier studies, interresponse dependencies in the current data were analysed by computing the average latency of RT2 as a function of relative speed of RT1 within its own distribution. Figure 7, Panels A-E present the mean eye (or vocal) RT2 as a function of the quintile in which the corresponding manual RT1 fell (with respect to the other manual responses for that subject and SOA), for Experiments 1-5, respectively. To compute this, for each subject, for each SOA, the manual responses were ranked and divided into five quintile bins (i.e. fastest to slowest trials). Then the latency of the eye movement (or vocal) response corresponding to the manual responses in each quintile was averaged. The mean across subjects was then computed.

Panels A and B (Experiments 1 and 2) show only a small dependency between the two response times. By contrast, Panels C and D (Experiments 3 and 4) show obvious and strong dependencies, interacting with SOA: the shorter the SOA, the greater the dependency. This was also observed in the earlier studies (e.g. Pashler, 1989).

A statistical analysis showed that even some of the dependencies that appear minimal in the figure are nonetheless significant. Panel A shows that there is little association between the relative speed of the manual response and the speed of the saccade in the first experiment. An analysis of variance with SOA and quintile as factors showed no effect of quintile, but there was a significant interaction of SOA with quintile, $F(24, 168) = 1.60$, $p < 0.05$. For Experiment 2 (Panel B), the effect of quintile was modest in size but significant, $F(4, 28) = 8.3$, $p < 0.001$. The interaction of quintile with SOA was also significant, $F(24, 169) = 1.9$, $p < 0.05$. For Experiment 3 (Panel C), the effect of quintile was much greater in mag-


A. Saccade to Spot

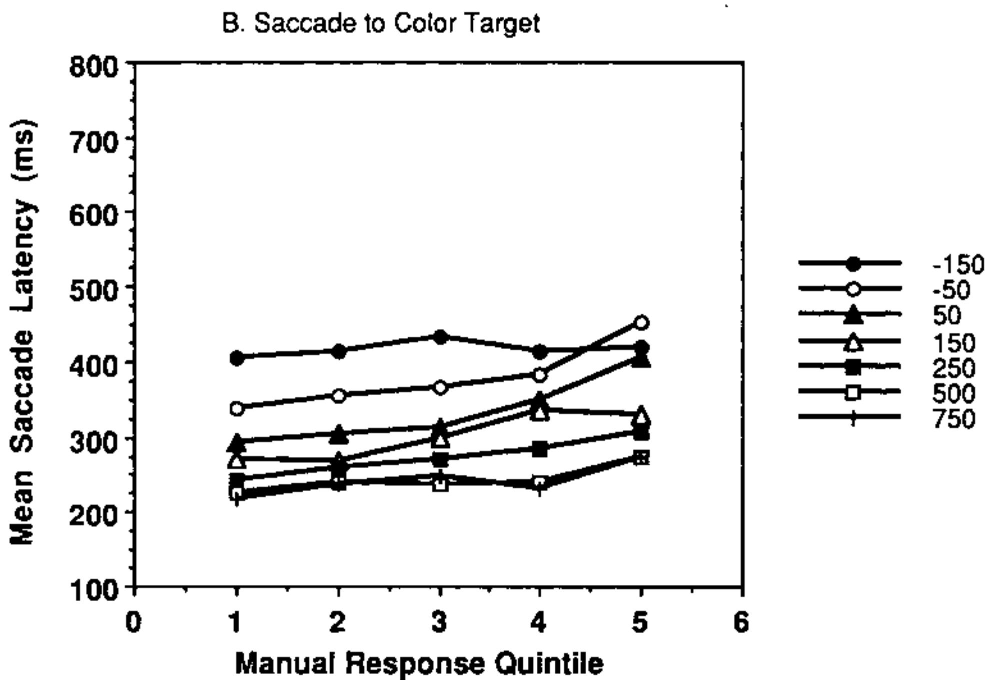
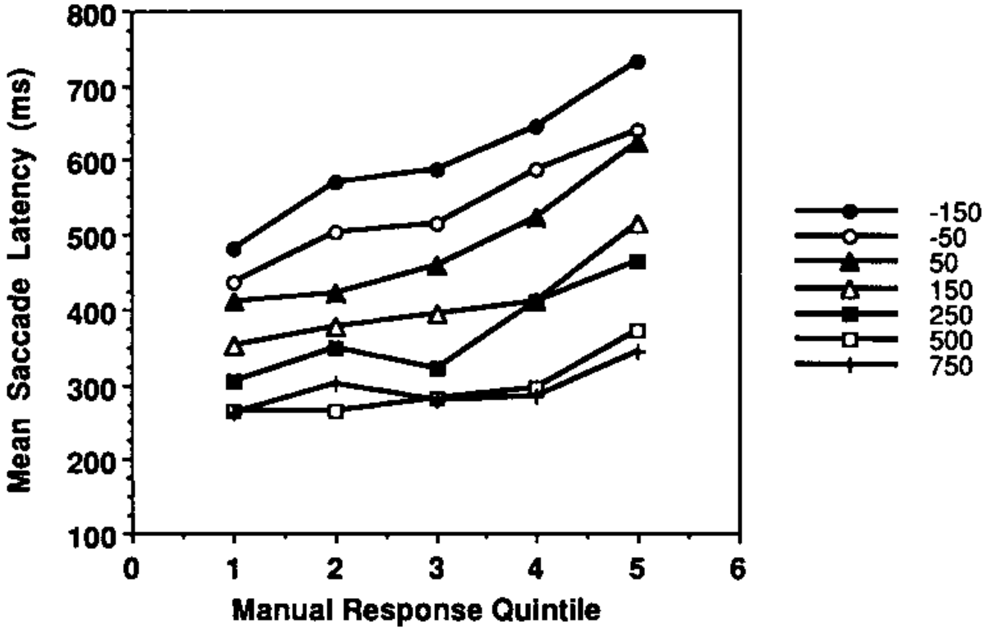
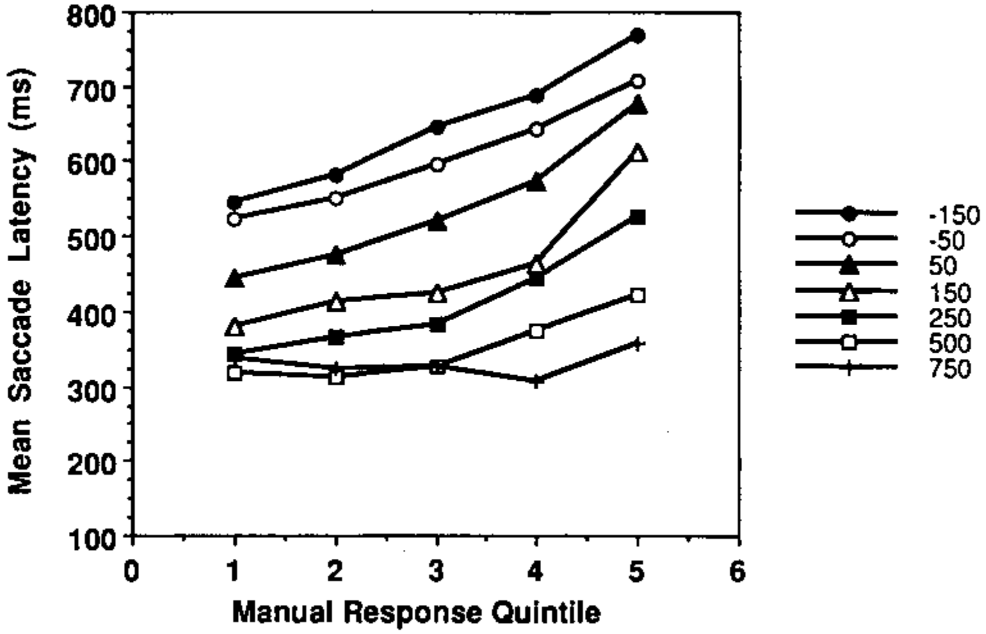

B. Saccade to Color Target

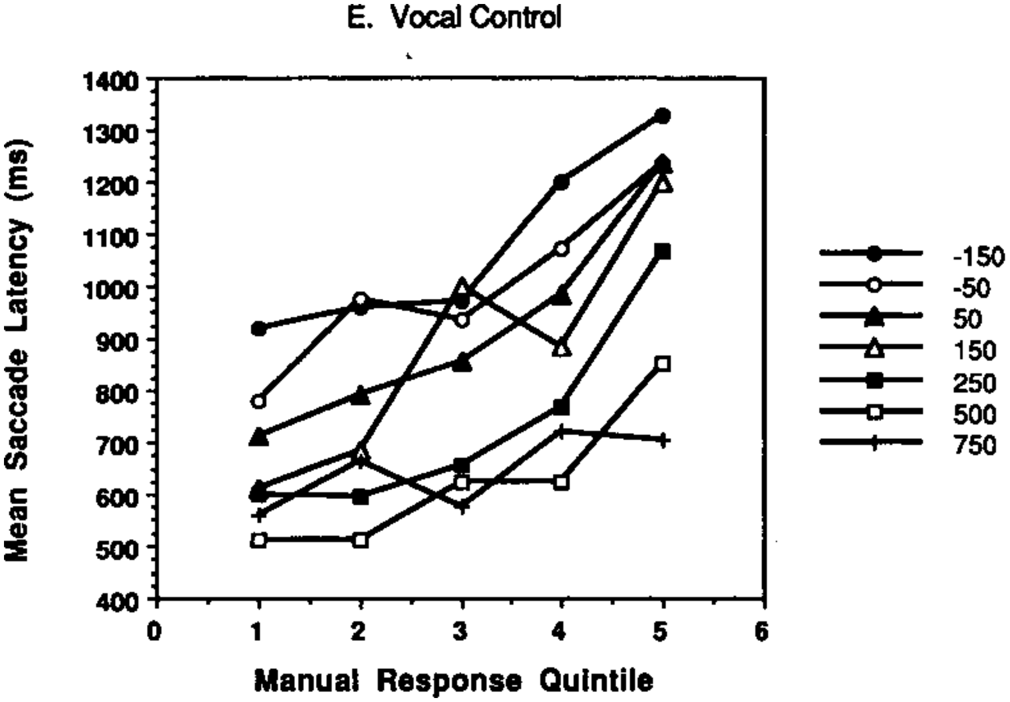
FIG. 7. Panels A-D: Mean eye movement latency as a function of which quintile the corresponding manual response fell in for that subject and SOA. Panel E: same vocal response in Experiment 5.

C. Saccade from Central Color



D. Saccade to Highest Digit





nitude, and it was significant, $F(4, 28) = 38.3$, $p < 0.001$. The Quintile X SOA interaction was significant, $F(24, 168) = 2.1$, $p < 0.005$. For Experiment 4 (Panel D), the effect of quintile looked very much like that of Experiment 3 and was significant, $F(4, 28) = 18.2$, $p < 0.001$. The Quintile X SOA interaction was again significant, $F(24, 168) = 4.2$, $p < 0.001$. For the vocal-manual control of Experiment 5, shown in Panel E, the quintile effect was significant, $F(4, 28) = 16.6$, $p < 0.001$, as was the expected Quintile X SOA interaction, $F(24, 168) = 1.7$, $p < 0.05$.

Interpretation

The detailed analysis of the five dual-task combinations examined here favours the view that was suggested by the mean RTs: that in the task combinations used in Experiments 3 and 4 (namely, the tasks of moving from the central colour patch, and moving to the highest digit), some operation(s) involved in generating the eye movements must wait for some aspect of the auditory/vocal task. That is, the tasks show evidence of a bottleneck. On the other hand, moving the eye to the single spot or moving it to the colour target seem to be virtually free of such bottleneck effects (although not entirely free of interference).

It would be inaccurate, however, to dismiss the residual interference observed with the first two saccade tasks, for it may turn out to be of theoretical interest. The source of this interference cannot be pinpointed from these experiments, but the data do bear on certain hypotheses.

(1) One might have supposed that eye movements are greatly delayed by the manual task, though only on a small fraction of trials, but the IRI distributions reject such a conjecture. (2) The fact that *some* slowing was associated with SOA even in the control condition of Experiment 2 (where there was no tone task) suggests that some of the effect is probably attributable to temporal uncertainty, i.e. at the long SOAs the subject has some more reason to expect the imminent arrival of the stimulus than at the short SOAs.

Further Comparisons of Experiments 3, 4, and 5

Nonetheless, the data do raise some interesting puzzles. On the one hand, Experiments 3 and 4 show the telltale signs of postponement: second-task slowing (the PRP effect) and dependencies between eye movement latencies and manual response latencies, which are modulated by SOA in the usual way. On the other hand, the interresponse intervals here are remarkably short. In fact, as Figure 6 (Panels C and D) indicate, on a good proportion of the trials at short SOAs the eye movement actually precedes the manual response.

The contrast with the results of Experiment 5 (manual-vocal control) is striking. In this experiment, instead of moving the eye left or right in response to the colour of a central patch, the subject said "left" or "right", and here the vocal responses occurred an average of about 350 msec *after* the manual response, rather than simultaneously with it. Furthermore, in Experiments 3 and 4, the slope of the function relating RT2 to SOA does not become as steep as minus one, whereas it comes very close to that value in Experiment 5.

These facts require one to conclude that the stages in the vocal task of Experiment 5 that are delayed by the bottleneck are much more time-consuming than are the bottleneck-dependent operations in the saccade tasks of Experiments 3 and 4. Actually, the magnitude of the PRP effect in Experiment 5 seems a bit larger than what is typically observed with task combinations that would appear to be comparable in "complexity" or "difficulty". This might be due to the fact that the experiment maps visual stimuli onto vocal responses, and auditory stimuli onto manual responses. This kind of mapping has been found to be particularly difficult in both single-task situations and in continuous dual-task performance (e.g. Shaffer, 1975), and one might hypothesize that such mappings are difficult to prepare, with the result that the response selection stages are particularly time-consuming.

In Experiments 3 and 4, on the other hand, the IRIs observed at short SOAs seem much shorter than those found in just about any highly compatible pair of classification tasks (see Pashler & O'Brien, in press, for some comparable cases). Consequently, one must conclude that the oculomotor task occupies the bottleneck mechanism only extremely briefly, compared to what occurs in other kinds of tasks. This conclusion (and other differences between the experiments) are discussed in somewhat greater detail below.

GENERAL DISCUSSION

In the first four experiments reported above, subjects made a manual response to a tone and a saccadic eye movement in response to a visual stimulus. The data present several clear results that rule out certain theoretically important claims, and they also present a number of puzzles that are not so easily accounted for in the general theory of dual-task interference sketched in the introduction. We begin with the clear results.

(1) The results rule out any suggestion that eye movements are free of interference from unrelated tasks that involve quite different sorts of motor responses. In all four experiments, the eye movement was significantly delayed as the SOA was reduced. In Experiments 3 and 4 (eye movements triggered by the central colour patch and by the highest digit, respectively), this interference was quite substantial, and the dependencies between the two response latencies showed the usual indices of postponement.

(2) The results of the first two experiments show that certain oculomotor tasks (saccade to the spot, and to the target colour) do not show the usual pattern of dual-task interference encountered with manual, vocal, and foot responses (e.g. Pashler, 1989, 1990; Pashler & Christian, 1991). In Experiments 1 and 2, there was little evidence that the second response was waiting for the first task: dependencies between R1 and R2 latencies were very weak, and at the short SOAs the order of the two responses was reversed without any slowing of the manual response that occurred second. This is quite different from what is usually observed with other sorts of tasks that have been investigated (with the possible exception of shadowing; see McLeod & Posner, 1984).

Do More Difficult Tasks Yield More Interference?

Despite these fairly clear-cut implications, the data also pose some intriguing puzzles. (1) There *was* statistically significant slowing of the eye movement responses (as SOA was reduced), even with the eye movements to the spot (Experiment 1) and to the target colour (Experiment 2). Some of this seems to be due to temporal uncertainty (as shown in the control condition of Experiment 2), but not all of it. (2) The effect of SOA on the eye movements in response to the central colour patch (Experiment 3) or the highest digit (Experiment 4) were much less than that observed with the vocal response (Experiment 5), resulting in much longer IRIs in the latter case.

How are these various degrees of interference to be understood? It may be useful to start by considering one very tempting way of summarizing the results of all the experiments: the second tasks that are more difficult show more interference. Indeed, if one uses mean RT2 (at the longest SOA) as an index of difficulty—which seems reasonable enough—then one does see an increase in difficulty as one proceeds from Experiment 1 to Experiment 5, and the slowing induced by SOA (RT2 at shortest SOA minus RT2 at longest SOA) increases accordingly. To put it differently, SOA and task difficulty show an *overadditive* interaction.

Thus, the results might illustrate the generalization that more difficult second tasks show more interference. This generalization certainly sounds very plausible. The only problem with it is that it is not a valid generalization: of all of the published experiments that have investigated dual-task interference using difficulty manipulations on non-oculomotor second tasks, none (that we are aware of) supports the generalization (see, for example, Karlin & Kestenbaum, 1968; Smith, 1969; Pashler, 1984; Pashler & Johnston, 1989; McCann & Johnston, 1992; Fagot & Pashler, in press). The generalization predicts overadditive interactions in RT2 latency between SOA and Task 2 difficulty, but the experiments cited (and other unpublished studies conducted in our laboratory) all show additive or underadditive interactions.

As noted in the introduction, if response delays are caused by a bottleneck in processing that begins at a critical stage of the second task, then difficulty factors slowing stages of the second task that are located before the bottleneck should produce underadditive interactions, whereas difficulty factors slowing stages at or after the bottleneck should produce additive effects. Thus the many findings cited in the list above can be readily understood in such a framework.

There are at least two different kinds of models that could account for overadditive interactions, when they do occur (as in the present situation). Within the bottleneck framework, suppose that a second task manipulation does not merely *prolong* some existing stage, but, rather (or in addition), it *inserts* an extra stage early in the second task that is delayed by the first task. That is, one supposes that in the difficult condition the second task requires the "bottleneck mechanism" *earlier* than it requires it in the easy condition. Any such manipulation will slow down the second task more at short SOAs than it will at long ones.

The second sort of account that could account for such effects is capacity sharing (e.g. McLeod, 1977b); if both tasks draw on limited capacity, then increasing the capacity demands of a task may increase dual-task interference (i.e. SOA effects). Hence, on certain assumptions, one might observe an overadditive interaction. The fact that such effects have not been observed previously has provided one reason for doubting capacity-sharing models (Pashler, 1984). As noted above, it might seem that capacity sharing would provide a reasonable account for the results of all five experiments: more difficult tasks require more capacity and therefore suffer more when the tone task is soaking up capacity. However, just about any capacity-sharing hypothesis is flatly contradicted by the fact that the manual response is significantly *faster* at short SOAs than at longer ones. This favours accounts within the family of bottleneck models.

A Tentative Account

On this basis, then, we can offer a tentative analysis of the time-course of processing in these five experiments. The oculomotor tasks in the first two experiments show little evidence of postponement. The speed of the first response has little effect on the speed of the second response, and the order of responding switched without apparently perturbing the manual response. These results are quite unlike those encountered with the numerous non-oculomotor tasks that have been combined with the tone/ button-push task. It seems clear, therefore, that these eye movement tasks do not require the central bottleneck mechanism of response selection.

Why, then, is there a little bit of slowing at shorter SOAs? Some of the slowing is probably due to the effects of temporal uncertainty, as demonstrated in the control condition of Experiment 2. This does not seem to account for all of the effect, however. One possibility is that the warning interval effect might somehow be amplified by the presence of the first task. Another possibility is that the tone task slows the eye movement response by producing a non-specific disruption of the task. Rather than the eye movement task "stealing capacity" away from the manual task, it may simply be the case that when the tone task is underway, the efficiency of the oculomotor system is reduced. The idea of capacity sharing—that one task's loss should be the other task's gain—may characterize human performance at a global level, but it may not hold when performance is examined at a more microscopic level (see Pashler, 1989, for a discussion).

What, then, of the slowing in the oculomotor tasks of Experiments 3 and 4? Here, the eye movement response showed a greater slowing with SOA than it did in Experiments 1 and 2, and there were strong positive dependencies between the speed of the manual response and the speed of the eye movement. Given these indices of postponement, it seems that these eye movement tasks *do* depend on the central response selection mechanism that creates a bottleneck in such a wide variety of tasks (Pashler, 1992). However, the IRIs are often negative, so these tasks must occupy this mechanism for a very short time compared to the vocal-manual control of Experiment 5 or to other comparable situations involving non-oculomotor tasks. Given the fact that the effect of SOA is smaller in

Experiments 3 and 4 than it is in Experiment 5, it may (as noted above) be the case that the vocal-manual task of Experiment 5 also occupies this bottleneck mechanism somewhat *earlier* in processing than do the oculomotor tasks of Experiments 3 and 4.[2]

Possible Physiological Bases

Assuming, then, that the eye movement tasks of Experiments 3 and 4 do depend on the central response selection mechanism (albeit briefly), it is reasonable to ask *why* the eye movement tasks in the first two experiments can be carried out without it? Psychological concepts like S-R compatibility or ideomotor compatibility (Greenwald & Shulman, 1973) do not provide much of an explanation. It may be that the explanation lies in the organization of different neural pathways involved in eye movements. Recent physiological work has distinguished two systems in the primate brain controlling saccades. One system originates in the superior colliculus (SC), and the other in the frontal eye fields (FEF) and associated frontal structures (including the supplementary motor area). Both project to the reticular formation of the brainstem (Harting, 1977), which contains burst cells that appear to trigger saccades directly.

Lesions of either the SC or the FEF alone do not prevent saccadic eye movements in the macaque (e.g. Schiller, Sandell, & Maunsell, 1987). However, when *both* structures are lesioned, visually guided saccades are virtually abolished (Schiller, True, & Conway, 1980). Cooling both also produces severe disruptions (Keating & Gooley, 1988). Eye-movement-related responses of single neurons have been recorded in both the SC (Sparks, 1986; Wurtz & Albano, 1980) and the FEF (Wurtz & Mohler, 1976), and saccades can be elicited by stimulation of both the SC (Schiller & Stryker, 1972) and the FEF (Robinson & Fuchs, 1969).

The SC pathway is generally regarded as critical in "reflexive" eye movements, but there is reason to suspect that it may be capable of more than that. In fact, it may be capable of generating responses of the sort required in both Experiment 1 and Experiment 2 (which involved a colour discrimination). Although the SC does not seem to receive direct information from retinal colour-opponent mechanisms (Schiller & Malpeli, 1977), nonetheless it was observed by Ottes, van Gisbergen, and Eggermont (1987) that SC neurons fired in close correlation with eye movements when monkeys performed a task very much like Experiment 2, in which a saccade

---

[2] An attempt to construct a rough quantitative model consistent with the means yielded the estimate that bottleneck-dependent processing in Task 2 of Experiment 3 might last about 100 msec, with about 150 msec-worth of pre-bottleneck processing. By contrast, in Experiment 5, the corresponding estimates were 350 msec and 100 msec, respectively. Such a deterministic model is, however, unrealistic. One difficulty confronting any quantitative model is the fact that the RT2/SOA functions in Experiments 3 and 4 do not show acceleration of the sort one would expect; this might be just a statistical anomaly.

was made towards a colour-defined target. It seems likely that the SC receives colour-related information along pathways that project to it from different areas in visual cortex (Finlay, Schiller, & Volman, 1976).

By contrast, the saccadic tasks that showed dual-task interference (Experiments 3 and 4) seem more like the sorts of eye movements for which the FEF is critical. Guitton, Buchtel, and Douglas (1985) studied patients with substantial frontal lesions usually including the FEF region, requiring them to perform either a "pro-saccade" task (saccade towards a cue), or an "anti-saccade" task (saccade away from a cue). A target appeared 300 to 600 msec after the cue. The patients were dramatically impaired in the anti-saccade task. On many trials, they erred by making a saccade towards rather than away from the cue. When correct anti-saccades were made, they usually did not occur until the target itself was present. Hence the responses were really pro-saccades to the targets rather than anti-saccades to the cues. Guitton et al. noted that these saccades came very quickly after the target appeared, from which they inferred that the eye movements were "organized" without the FEF. They suggested that the role of the FEF was simply to "release" saccades directed away from stimuli present at the time. As noted earlier, the results of Experiments 3 and 4 suggest that the "bottleneck-dependent" processes in these tasks are also extremely brief, so these results are consistent with the conjecture that the bottleneck-dependent processes might just *be* the operations that are carried out by the FEF.

Obviously, it would be very helpful to know whether patients with FEF lesions can perform saccades based on a central colour cue (Experiment 3), or saccades to the highest digit (Experiment 4). Based on the suggestions above, it would be predicted that they could not. In the absence of such evidence, it is simply a conjecture that perhaps those eye movements that are mediated by the SC are largely exempt from dual-task interference, whereas those dependent upon the FEF show "bottleneck dependency". The possibility that central dual-task interference might originate in frontal structures is broadly consistent with the picture that emerges from studies of patients with frontal damage. For instance, frontal-damage patients have been found to have difficulty in switching between different task sets (see Shallice, 1988, for a review). In addition, the responses of neurons in frontal areas of macaque monkeys suggest that these neurons are involved in selection of arbitrary manual responses much like those investigated in conventional PRP studies (Requin, Riehle, & Seal, 1988), although it should be noted that other cortical regions also seem to be involved.

Questions and Implications

Another interesting question raised by these results concerns the possibility that other very basic sensorimotor behaviours are (relatively) free of interference from ongoing tasks, as the saccadic tasks of Experiments 1 and 2 are. McLeod and Posner (1984) report that shadowing appears to be such a task. Visually guided manual reaching is another obvious candidate, but we recently found dual-task interference when combining reaching with an easy auditory-vocal choice task (Pashler & Christian, 1991). Given the wide range of tasks that are now known to produce PRP-type interference, cases like shadowing and (certain) saccades seem likely to remain the exception, rather than the rule.

Finally, the results have implications for analysing human performance in demanding real-world tasks such as aviation or driving. Based on the results of the first two experiments (and those of Pashler, 1989), it seems likely that an automobile driver can detect a threatening peripheral stimulus (e.g. a looming pedestrian) and execute a saccade to obtain more information about it while carrying out some concurrent task, such as planning a spoken utterance. This independence might be critical in enabling people to perform as well as they do in many common and practically important activities.

REFERENCES

Davis, R. (1959). The role of "attention" in the psychological refractory period. *Quarterly Journal of Experimental Psychology,* 77, 211-220.

Fagot, C., & Pashler, H. (in press). Making two responses to a single object: Exploring the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance.*

Finlay, B.L., Schiller, P.H., & Volman, S.F. (1976). Quantitative studies of single-cell properties in monkey striate cortex. IV. Corticotectal cells. *Journal of Neurophysiology, 46,* 755-772.

Gottsdanker, R. (1980). The ubiquitous role of preparation. In G.E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 355-372). Amsterdam: North-Holland.

Greenwald, A.G., & Shulman, H.G. (1973). On doing two things at once: II. Elimination of the psychological refractory period effect. *Journal of Experimental Psychology, 101,* 70-76.

Guitton, D., Buchtel, H.A., & Douglas, R.M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research, 58,* 455-472.

Harting, J.K. (1977). Descending pathways from the superior colliculus: An autoradiographic analysis in the rhesus monkey *(Macaca mulatto). Journal of Comparative Neurology, 173,* 583-612.

Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology, 20,* 167-178.

Keating, E.G., & Gooley, S.G. (1988). Saccadic disorders caused by cooling the superior colliculus or the frontal eye field, or from combined lesions of both structures. *Brain Research, 438,* 247-255.

Kleiss, J.A., & Lane, D.M. (1986). Locus and persistence of capacity limitations in visual information processing. *Journal of Experimental Psychology: Human Perception and Performance,* 72, 200-210.

Kowler, E., & Zingale, C. (1985). Smooth eye movements as indicators of selective attention. In M.I. Posner & O.S.M. Marin (Eds.), *Attention and performance XI: Mechanisms of attention* (pp. 285-300). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

McCann, R.S., & Johnston, J.C. (1992). The locus of the single channel bottleneck in dual task interference. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 471-484.

McLeod, P. (1977a). A dual task response modality effect: Support for multiprocessor models of attention. *Quarterly Journal of Experimental Psychology, 29,* 651-667.

McLeod, P. (1977b). Parallel processing and the psychological refractory period. *Acta Psychologica, 41,* 381-391.

McLeod, P., & Posner, M.I. (1984). Privileged loops from percept to act. In H. Bouma & D.G. Bouwhuis (Eds.), *Attention & performance X.* Hove: Lawrence Erlbaum Associates Ltd.

Malmstrom, F.V., Reed, L.E., & Weber, R.J. (1983). Saccadic eye movements during a concurrent auditory task. *Bulletin of the Psychonomic Society, 27*, 31-34.

Mather, J.A., & Fisk, J.D. (1985). Orienting to targets by looking and pointing: Parallels and interactions in ocular and manual performance. *Quarterly Journal of Experimental Psychology, 37A,* 315-338.

Mather, J.A., & Putchat, C. (1983). Parallel ocular and manual tracking responses to a continuously moving visual target. *Journal of Motor Behavior, 15,* 29-38.

Megaw, E.D., & Armstrong, W. (1973). Individual and simultaneous tracking of a step input by the horizontal saccadic eye movement and manual control systems. *Journal of Experimental Psychology, 100,* 18-28.

Oster, P.J., & Stern, J.A. (1980). Electrooculography. In I. Martin & P.H. Venables (Eds.), *Techniques in psychophysiology* (pp. 275-309). New York: Wiley and Sons.

Ottes, F.P., van Gisbergen, J.A.M., & Eggermont, J.J. (1987). Collicular involvement in a saccadic colour discrimination task. *Experimental Brain Research, 66,* 465-478.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 358-377.

Pashler, H. (1989). Dissociations and dependencies between speed and accuracy: Evidence for a two-component theory of divided attention in simple tasks. *Cognitive Psychology, 21*, 469-514.

Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention? *Journal of Experimental Psychology: Human Perception and Performance, 16,* 826-842.

Pashler, H. (1991). Visual selective attention and the two-component theory of divided attention. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 1023-1040.

Pashler, H. (1992);. Dual-task interference and elementary mental mechanisms. In D. Meyer & S. Kornblum (Eds.), *Attention and performance XIV.* Cambridge, MA: MIT Press.

Pashler, H., & O'Brien, S. (in press). Dual-task interference and the cerebral hemispheres. *Journal of Experimental Psychology: Human Perception and Performance.*

Pashler, H., & Christian, C. (1991). *Motor response production and dual-task interference.* Unpublished manuscript.

Pashler, H., & Johnston, J.C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology, 41 A,* 19-45.

Requin, J., Riehle, A., & Seal, J. (1988). Neuronal activity and information processing in motor control: From stages to continuous flow. *Biological Psychology, 26,* 179-198.

Robinson, D. A., & Fuchs, A.F. (1969). Eye movements evoked by stimulation of the frontal eye fields. *Journal of Neurophysiology, 32,* 637-648.

Schiller, P.H., & Malpeli, J.G. (1977). Properties and textal projections of monkey retinal ganglion cells. *Journal of Neurophysiology, 40,* 428-445.

Schiller, P.M., Sandell, J.H., & Maunsell, J.H.R. (1987). The effect of frontal eye field and superior colliculus lesions on saccadic latencies in the rhesus monkey. *Journal of Neurophysiology, 57*, 1033-1049.

Schiller, P.H., & Stryker, M. (1972). Single-unit recording and stimulation in superior colliculus of the alert rhesus monkey. *Journal of Neurophysiology, 35*, 915-924.

Schiller, P.M., True, S.D., & Conway, J.L. (1980). Deficits in eye movements following frontal eye-field and superior colliculus ablations. *Journal of Neurophysiology, 44,* 1175-1189.

Shepherd, M., Findlay, J.M., & Hockey, G.R.J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology, 38A,* 475-491.

Shaffer, L.H. (1975). Multiple attention in continuous verbal tasks. In P.M.A. Rabbitt and S. Dornic (Eds.), *Attention and performance V* (pp. 157-167). New York: Academic Press.

Shallice, T. (1988). *From neuropsychology to mental structure.* Cambridge: Cambridge University Press.

Smith, M.C. (1969). The effect of varying information on the psychological refractory period. *Acta Psychologica, 30,* 220-231.

Sparks, D.L. (1986). Translation of sensory signals into commands for control of saccadic eye movements: Role of primate superior colliculus. *Physiological Review, 66,* 118-171.

Welford, A.T. (1952). The "psychological refractory period" and the timing of high speed performance: A review and a theory. *British Journal of Psychology, 43,* 2-19.

Wurtz, R.H., & Albano, J.E. (1980). Visual-motor function of the primate superior colliculus. *Annual Review of Neuroscience, 3,* 189-226.

Wurtz, R.H., & Mohler, C.W. (1976). Enhancement of visual responses in monkey striate cortex and frontal eyefields. *Journal of Neurophysiology, 39,* 766-772.

Revised manuscript received 9 July 1992