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Do Response Modality Effects Support Multiprocessor Models of Divided Attention?

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Some-studies have suggested that dual-task interference is greatly reduced when tasks requiring very different types of responses (e.g.. manual and vocal) are combined. However, in those studies, the order of stimuli varied unpredictably. In Experiments 1 and 2, variable stimulus order greatly inflated interference between two manual tasks, whereas interference between a manual and a vocal task was only slightly exacerbated. However, central interference (the psychological refractory period) persisted even with the manual/vocal combination. Selection of 2 manual responses with unknown stimulus order may require a special strategy to preclude intertask intrusion errors. Experiment 3 demonstrated that such errors could be provoked with speed stress. Together, these results reconcile response modality effects with the response selection bottleneck model for dual-task interference (once it is suitably amended).

The field of divided attention covers a wide range of phenomena. Much research has focused on the limitations that arise when people attend to multiple sensory stimuli, making a single response dependent upon the nature of these stimuli. A typical laboratory task in that area is visual search, and the focus is on the mechanisms involved in the recognition of features and objects. Another traditional field of divided attention research deals with interactions between two different tasks, each requiring selection and execution of a separate action. Performance impairments are ubiquitous when two tasks are combined. In fact, interference is so easy to observe that cases in which interference may not arise (i.e., in which several tasks seem to proceed independently) are of special interest. This interest is well justified because the boundaries of task independence may provide clues about which cognitive processes depend upon particular crucial mental mechanisms and which do not. Tracing these boundaries is therefore a promising strategy for uncovering the basic functional architecture of human cognition. Such work is also of practical value by allowing optimal equipment design in fields such as aviation where people must make rapid and accurate responses to important stimuli that can occur arbitrarily close together in time. The purpose of the present work is to critically examine previous claims that varying the response modalities used in dual-task experiments can drastically reduce interference between tasks. This article suggests that these claims are overstated and proposes an explanation for response modality effects consistent with the analysis of dual-task interference proposed earlier by the author (Pashler, 1984, 1989; Pashler & Johnston, 1989).

Single-Channel Models

Simultaneous performance of multiple tasks has been investigated in a wide variety of situations. Much work in this area focuses on complex tasks performed over extended periods of time. The results are often intriguing and have practical implications, but there are limits on how much they can reveal about the underlying causes of interference (see Pashler, 1989, for a discussion). The focus of the present work is on very simple tasks in which the time course of processing in both tasks can be analyzed. Naturally, one cannot assume that in very simple tasks one will encounter all of the factors that can produce (or mitigate) interference in more complicated situations. Nonetheless, they are surely the rational place to start. The simplest situation in which dual-task performance can be studied in detail involves presentation of two stimuli (S1 and S2), with a separate response being made to each (R1 and R2, respectively). The interval between the onset of the stimuli (stimulus onset asynchrony, or SOA) is varied by the experimenter. This paradigm is traditionally referred to as the "psychological refractory period" (PRP) paradigm in reference to the characteristic slowing of the second response time (RT2) observed as the SOA is reduced. The PRP paradigm potentially provides a rich source of information, because one can observe response latencies on both tasks, and examine how the latency of each response is related to performance on the other task. The PRP paradigm was extensively investigated in the 1950s and 1960s (see Smith, 1967, for a review), but has been much less commonly studied recently. Perhaps this is because of the difficulty experienced by early researchers in achieving quick closure on some disputed issues. Whatever the reason, neglect of the PRP paradigm has slowed progress toward the goal of characterizing dual-task interference in real time.

Several crucial and robust observations were made during the early period of research on the PRP phenomenon. These

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results were roughly captured by the "single channel model" of Welford (1952, 1980). According to this view, certain stage(s) of processing in each task require that a single mechanism be devoted to them. Thus, when that critical mechanism is involved in servicing the first task, the corresponding stages of the second task are postponed. Welford, among others, suggested that even the simplest decision and response selection operations were subject to postponement, whereas perceptual and motor execution stages could operate without this restriction. However, other writers (e.g., Keele, 1973) suggested that initiation of motor responses, but not the central cognitive stages, were subject to postponement in choice tasks. Still other writers proposed that in general both tasks draw upon a limited pool of resources, sharing these resources in a graded manner (Kahneman, 1973). Interference in both tasks was explained by supposing that the efficiency with which each task can be performed is proportional to the amount of capacity allocated to it.

Recent work by the author, however, has provided detailed evidence for response selection postponement in simple dual-task situations. This work (Pashler, 1984; Pashler & Johnston, 1989) used chronometric methods for testing distinctive predictions derived from particular bottleneck models. These experiments are somewhat complex, but the basic idea and the general results can be briefly summarized. Suppose—in line with single-channel postponement models—that responses to S2 are delayed because a particular Stage B in Task 2 must wait for the completion of Stage B in Task 1, whereas earlier stages (A) of Task *2* do not need to wait; they can begin as soon as S2 is available. Suppose, then, that an experimental manipulation is used to slow down Stage B in Task 2 by, say, 50 ms. Obviously, this slowing will show up as a 50-ms increase in RT2 (measured, by convention, from S2 to R2). On the other hand, suppose Stage A in Task 2 is slowed by 50 ms. This slowing should be eliminated in the dual-task situation with short SOAs, because now Stage B of Task 2 does not wait on the completion of Stage A, but rather on the completion of Stage B of Task 1, which generally occurs later. When different factors are manipulated, this method provides a way of testing different single-channel models, and can discriminate between single-channel models and alternatives like graded sharing of general capacity (Kahneman, 1973).

Initial attempts to use this logic in analyzing dual-task interference were inconclusive, because they used factors that did not have a clear locus of effect (Keele, 1973; Schweickert, 1978). This logic has been used in several more recent experiments, however, and the results support response selection postponement (Pashler, 1984; Pashler & Johnston, 1989). Factors relating to the second-task stimulus (S2) that are believed to affect the duration of second-task response selection had approximately the same effect upon RTs in the dual-task and control conditions. On the other hand, an S2 factor affecting the duration of perceptual processing had markedly reduced effects in the dual-task condition in several experiments (compared with its magnitude assessed in single-task conditions), and in the dual-task condition, these effects tapered off as SOA was reduced just as the postponement model predicts. These results clearly reject models such as Keele's response execution postponement account, and they are not consistent with general capacity sharing either. In more recent work, Pashler (1989) reported new converging evidence for response selection postponement based on entirely different kinds of analyses. This research examined dissociations in the effects of SOA on different measures of Task 2 performance—RT versus accuracy with brief masked presentations of S2—and also examined details of how response measures in the two tasks are related on a trial-by-trial basis.

The "Multiprocessor" Alternative

The experiments just described provided strong evidence for a "single-channel bottleneck" in response selection as the basic source of dual-task interference in simple overlapping tasks. How general is this conclusion? All of the experiments described previously involve two tasks each with a manual response. Consequently, the conclusions are vulnerable to a very well-known challenge to single-channel theories developed by several writers, especially Allport (e.g., 1979) and McLeod (e.g., 1977, 1978). In a series of incisive articles, both Allport and McLeod argued that single-channel models are profoundly flawed, and presented important empirical observations that seem to undercut such models. The basic point of the critique is that the evidence for a single-channel bottleneck stems from cases where the two tasks have very similar responses (as in all of the studies just cited). Allport, McLeod, and their collaborators also reported that when the two tasks use very different responses (e.g., a manual and a vocal response), dual-task interference can be eliminated or at least greatly reduced. We refer to the use of different response modalities as *response separation.*

The theoretical approach that Allport and McLeod proposed to replace the single-channel model is one they have termed the "multiprocessor" account. The basic idea is that when different kinds of responses are called for, quite independent cognitive systems are involved in performing the tasks: multiple processors. This allows independence between the performance of the two tasks. It is important to note that such independence does not entail that dual-task performance will be as good as single-task performance, but only that the two tasks will be free of temporal interactions (i.e., SOA effects or dependencies between the two tasks). Direct comparisons of single- and dual-task performance are not discussed much in this article. Some generalized impairment of dual-task performance compared with single-task performance is ubiquitous (even when the tasks do not actually overlap at all), but it is not theoretically informative. It may often reflect simply a failure in the dual-task condition to optimally prepare in advance those procedures required for performing both tasks (see Gottsdanker, 1980; Logan, 1978; Pashler & Johnston, 1989). Such generalized interference is consistent with either single-channel or multiprocessor models. For these reasons, effects of response separation on dual-task interference are examined by studying temporal dependencies within dual-task situations rather than generalized decrements from single- to dual-task performance.

According to the view proposed by Allport and McLeod, then, dual-task interference can be eradicated when different response modalities recruit different processors for the two tasks. On the other hand, tasks with similar responses are predicted to show results suggestive of a single-channel bottleneck. According to this view, it is a mistake to associate dual-task interference with particular stages of processing. Rather, the crucial factor is held to be the similarity of the tasks, and especially the similarity of the responses.[1]

The work mentioned has been influential in producing the current widespread skepticism about single-channel models (see, e.g., Hirst, 1986; Norman & Shallice, 1985). We begin by reviewing the empirical work that has been seen as challenging single-channel models. The studies are reviewed in detail to bring out two points not previously noted in the literature: (a) that there is no conclusive evidence that single-channel type interference between tasks can actually be *abolished* by using very different responses, so long as both tasks require stimulus-dependent response selection and execution; and (b) that response separation seems to have the most pronounced effects when the order of stimuli is unpredictable to the subject. Predictability of stimulus order is a factor that has apparently never been varied within an experiment or discussed in the literature; this is rectified by the experiments presented later.

Evidence Against Single-Channel Effects From Studies Using Dissimilar Responses

Probably the most widely cited challenge to postponement models was presented by Allport, Antonis, and Reynolds (1972), in an article provocatively subtitled "Disproof of the Single-Channel Hypothesis." The basic finding pertained to the ease with which shadowing could be combined with other tasks, when the other tasks used very distinct stimulus or response modalities. In one experiment, fairly experienced pianists shadowed while sight-reading piano music, and by their second session, neither task suffered more than very mild dual-task interference. Obviously, these results are of major importance, particularly if one accepts the supposition that tasks like shadowing must fully and continuously occupy any single-channel mechanism. However, the tasks are complicated and allow preview of the stimulus material. Therefore, as Broadbent (1982) suggested, successful dual-task performance may reflect a strategy involving switching between tasks. After all, auditory stimuli are preserved in a sensory buffer that lasts for several seconds, and for practiced subjects such as these responses might be selected in large "chunks" that might take as much as a second or two to produce. The piano task may similarly depend upon buffering and chunking. If so, the minimal interference observed might still be consistent with a single-channel response selection mechanism that operates in a strictly sequential manner.

To assess such possibilities, it is necessary to study situations in which preview is not available, and in which temporal dependencies between performance and individual stimulus-response latencies can be analyzed in detail. McLeod investigated cases of this sort with much ingenuity. McLeod (1977) presented one of the clearest arguments that dual-task interference among simple tasks arises only when both tasks use the same response modality. Two tasks were combined in these studies. The first was a visual tracking task in which subjects used a joystick with one hand to control the horizontal position of a target on the screen, attempting to hold it to the center. The second task was a two-choice response to a tone. In the dual-task situation, the tone stimuli were presented at random intervals ranging from 1,500 to 2,500 ms (rectangular distribution) while the subject tracked continuously. In one condition, subjects made a manual response to the tone, pressing one of two buttons depending upon whether the tone was high or low in pitch (using the other hand). In the other condition, subjects made a vocal response, saying "high" or "low." The primary analysis involved the temporal pattern of tracking responses distributed about individual tone responses. Specifically, McLeod observed the intervals between the last tracking response before a given tone response, and the interval between a given tone response and the following tracking response. The distribution of these interresponse intervals in the dual-task situation was compared with a control distribution representing the hypothetical possibility that the two response streams were temporally independent. The latter distribution was generated in an ingenious way by arbitrarily aligning the response trains for two single-task controls as if they were produced in a dual-task situation. In this way, a subject's actual dual-response stream could be contrasted with what would have been observed were the streams free of mutual interference or interaction.

The results were clear-cut. On the one hand, the absolute level of tracking performance achieved was reduced in the dual-task situation. However, for the vocal response, the interresponse interval distributions did not differ between the dual-task and control conditions. Thus, the data indicated temporal independence between the two response streams. By contrast, for manual responses, dual-task and control distributions were quite different. There was a reduction in the frequency of short intervals (< 400 ms) between tracking response and tone response, and a corresponding increase in the frequency of intermediate (say, < 400 ms) intervals between tone responses and tracking responses. McLeod (1977) suggested that these reflected "the delay of some of the tracking responses which could have been made shortly before the two-choice response, had the processes been controlled by independent pools of processing capacity" (p. 659). From this, he concluded that "the vocal and manual responses are produced by independent processors, but the two streams of manual responses are produced by interacting processes" (p. 659).

The analysis is useful, but there may be serious problems with the tasks themselves. The tracking task involved a joystick controller, which could be in the left or right positions. In the left position, it induced an acceleration of $-8\ cm/s^2$, and in the right position, it induced an acceleration of +10

[1] Naturally, one could suggest this type of framework but argue that response modality does not determine whether the same processor is required for both tasks. Suggestions along these lines (e.g., Hirst & Kalmar, 1987; Navon & Miller, 1987) are discussed briefly in the General Discussion section, but the present focus is on response modality effects as distinct from other forms of task similarity.

cm/s^2. The subject's job was to change the positions in such a way as to hold the spot as close as possible to position zero. Subjects were given ample practice in this task. Note, therefore, that although the task may be difficult in some respects, it does not necessarily require the subject to use sensory information in the control of the tracking task. Indeed, the task could in principle be accomplished simply by alternating rhythmically between left and right positions, dwelling slightly longer in the left position than the right. Of course, it seems plausible that visual guidance would nonetheless be used to some degree, but one simply cannot say how much or how often. For this reason, then, the results may have little bearing on accounts like single-channel response selection postponement.

Wickens (1976) presented another set of results suggesting that visual-manual and auditory-vocal response streams could be performed without interference. Subjects combined a visual tracking task with several other tasks. The tracking task required the subject to counteract an effectively random input from the computer, and thus is not subject to the difficulties discussed in connection with McLeod's (1977) study. In the most relevant condition, the subject combined tracking with an auditory signal-detection task, requiring a vocal response. Tracking performance was compared in the single- and dual-task conditions. Overall tracking performance was reduced (about a 30% increase in root mean square error). More important, however, further analyses suggested that this was not due to any tendency for subjects to take time out of the tracking task, and therefore initiate tracking responses less frequently.[2] The analysis that indicated this was based on a quasilinear control theory model of tracking according to McRuer and Jex (1967). This model accounts for performance with three parameters, reflecting (roughly) the following: the frequency with which corrections are initiated, the magnitude of corrections, and a residual nonlinear noise factor. Basically, the decrease in performance produced by combining tracking with the signal-detection task took the form of an increase in the residual, with little decrease in the frequency of initiation of corrections.

Two comments can be made about this study. First, the analysis is sophisticated, but it is also heavily dependent upon the particular model used. There is reasonable evidence for the model, however, so it may be sensible to give it the benefit of the doubt for present purposes. The second and more serious problem, however, is the signal-detection task itself. Choice of response was not required, so the task may not require the crucial response selection processes discussed previously. In addition, it was not a speeded task. In fact, typical response latencies were in the 1-s range. Clearly, this is far in excess of the minimum required for such a task, and thus the data are perfectly consistent with the idea that subjects may delay selection of their vocal responses until central mechanisms are not occupied with the tracking task. Thus, again, the results could be consistent with many single-channel theories. (It should be noted that Wickens himself was apparently aware of some of these limitations in discussing the relation of his data to the single-channel view; see p. 10 ff.).

McLeod (1978) presented further evidence indicating that manual/vocal response combinations may be associated with reduced dual-task interference compared with manual/manual combinations. The study investigated the "probe RT" method of Posner and Boies (1971), and concluded by raising serious doubts about the assumptions of that method. As a primary task, subjects performed a same/different judgment on two letters presented in immediate succession, each for 500 ms, making a two-choice manual response. On half the trials, a burst of white noise sounded at a point in time ranging from 0.85 s before the onset of the first letter to 0.9 s after the onset of the second letter. Simple detection responses to the burst were manual for one group of subjects and vocal for another. Subjects were instructed to complete both tasks on dual-stimuli trials. Manual RTs to the noise burst were elevated when it sounded around the time of the onset of the second letter, as previously observed by Posner and Boies (1971). However, when the responses were vocal, no such elevation occurred. McLeod suggested that these observations invalidate the probe RT method of Posner and Boies. That method relied on the assumption that probe RTs provide a direct measure of the "spare capacity" available at any given moment during the performance of the primary task. Additional observations of McLeod's were also incompatible with this assumption. For instance, vocal probe RTs were quite unaffected by whether the letters matched or not, whereas mismatching letters were associated with faster manual probe RTs.

What is to be made of these results? The results certainly do call into question any assumption that probe RT provides a measure of so-called general capacity. What is not so clear, however, are the implications for single-channel models, and whether, as McLeod suggested, the results require multiprocessor models. The absence of an effect of timing on probe RTs is consistent with such a conclusion. However, there is another aspects of the results, reported but not discussed by McLeod, that undermines this. Latencies for the same/different response were substantially elevated when the probe came near the time of the second letter for vocal-response probes as well as manual-response probes. The elevation induced by the manual probes was larger, however. Overall, then, these results too suggest that modality differences can attenuate interference, but they do not suggest its eradication.

More recently, McLeod appears to have revised his view concerning the conditions under which single-channel limitations are eliminated. McLeod and Posner (1984) suggested that perhaps only the task of shadowing spoken input can completely bypass the interference associated with other tasks (perhaps because it may have a specialized neural substrate, e.g., the arcuate fasciculus, damage to which can produce conduction aphasia). In McLeod and Posner's study, the primary task was again letter matching, but different groups of subjects made different types of responses to spoken-word probes. These responses included shadowing (repeating a spoken single word) and arbitrary nonshadowing vocal responses. Letter-match RTs showed some interference when the stimuli

[2] As in the previous cases discussed here, overall impairment in dual-task compared with single-task performance is ubiquitous, but quite uninformative.

were close in time, but probe responses did not show the usual slowing when the probe called for a shadowing response. An earlier study of Greenwald and Shulman (1973) also seemed to find elimination of the PRP effect when one of the responses involved shadowing a spoken input. In the present article, we do not address the possibility that shadowing may be free of dual-task interference, but instead attempt to understand the basic response separation effects, and evaluate the multiprocessor interpretation advocated by Allport (1979) and McLeod (before his 1984 article); shadowing will be considered in subsequent reports.

Contrasting Perspectives on Response Modality

This review of the literature on response modality effects in dual-task attention suggests, first, that there is actually only rather weak and spotty evidence that separating the response modalities can actually *eradicate* dual-task interference even with very simple tasks. On the other hand, it seems clear enough that response separation may reduce the interference quite dramatically under certain circumstances. How can such observations be accounted for within the response selection postponement framework (Pashler, 1984; Pashler & Johnston, 1989) sketched earlier? There is no obvious explanation at hand, if all interference is presumed to stem from a bottleneck associated with central stages of processing, because these stages are contained in all choice tasks whatever their input and output modalities. The account preferred by Allport and McLeod suggests that separate processors control selection and execution of responses in different modalities. This could explain the complete absence of interference with response separation, but it cannot readily account for reduced interference. It might seem, though, that one need only suppose that, although there is one stage of processing that all choice tasks have in common, there is also another stage that is handled by different processors. These could be response selection and response programming and execution, respectively. Essentially, this account would be a hybrid single-channel and multiprocessor model. However, the chronometric evidence cited earlier can rule out this account. If response initiation in the second task is postponed while the corresponding stage of the first task proceeds, then PRP experiments with dual manual responses should show a washout of the effects of factors slowing any processing stages before response execution. In fact, however, such factors turn out to have effects that are basically additive with the overall dual-task slowing (Pashler, 1984; Pashler & Johnston, 1989).

Another possibility is that perhaps the studies reviewed previously here show substantial response modality effects for reasons other than the postponement envisioned by either single- or multichannel models. The author became interested in this possibility after performing some pilot experiments using an ordinary PRP task with one vocal and one auditory response. Reliable second-task slowing occurred; In fact, separation of response modalities did not appear to change the PRP effect much at all. Why would a PRP paradigm show little effect of modality separation given the various findings just reviewed (especially McLeod, 1977, 1978; McLeod & Posner, 1984) showing very large effects? What could the critical variable be?

One notable difference between the PRP situation and the studies reviewed in the preceding section pertains to whether the subject knows the order of the stimuli (and hence also the order of responding). In the PRP situation, the order is always fixed, whereas in the studies just reviewed, it varies from trial to trial. The multiprocessor account does not predict that this variable should be especially potent. According to that view, interference is a function of whether a particular task requires a common processor, which is in turn determined by the similarity of the responses. Perhaps knowledge of the order of stimuli allows the processor to begin work on a particular stimulus more quickly, but there is no obvious reason why this should interact with the similarity of responses.

As it happens, the effects of knowledge of the order of stimulus presentation in dual-task performance has not been directly studied. Such effects have obvious practical as well as theoretical importance. The first two experiments have two goals. One is to determine how subjects' knowledge of the order of stimuli affects or does not affect performance in a dual-task situation either with two manual responses (Experiment 1) or with a manual/vocal response combination (Experiment 2). The second goal is simply to see whether interference between tasks can be abolished or reduced by response separation in a design that rectifies the various problems noted in connection with earlier studies (e.g., Allport et al., 1972; McLeod, 1977, 1978; Wickens, 1976). To do this, we must examine latencies on both tasks as a function of the relative timing of stimuli, and determine the nature of interference and interdependences among the responses as a function of response separation. We use two choice tasks so that response selection is required on each task.

Experiment 1: Manual/Manual Responses

In the first experiment, subjects made two responses on each trial. One was a two-choice left-hand button-push response to a tone (high vs. low pitch), and the other was a three-choice right-hand button-push response to a letter (A vs. B vs. C). In some blocks, the tone always came first; in other blocks, the letter always came first; in still other blocks, the order was unknown to the subject. To remove any specific temporal warning of the onset of any stimulus, the warning interval between the fixation point and the first stimulus was randomly selected from a quasiexponential distribution.

Method

Subjects. Eighteen undergraduates at the University of California, San Diego, participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and stimuli. The stimuli were presented on Princeton Graphics SR-12 monitors controlled by IBM PC microcomputers (equipped with Sigma Design Color-400 boards, providing a display resolution of 640 x 400 pixels). One stimulus was a tone presented through the speakers on the monitors at 300 or 900 Hz. The duration of the tone was 100 ms. The second stimulus was a centrally positioned letter, an A, B, or a C. This character measured about 0.3 cm wide x 0.4 cm high, and it was presented for 400 ms. The subject viewed the display from a distance of approximately 60 cm. The display was presented in bright white on a black background and was viewed under normal room illumination.

Design. The experiment was divided into 9 blocks of 54 trials each. There were 3 types of blocks: tone-first, letter-first, and unknown order. In the tone-first blocks, the tone was always presented first, and the SOA separating it from the letter was 100, 200, or 700 ms. In each block of this type, there were 18 trials at each SOA. In tone-first and letter-first blocks, there were 18 trials at each of these SOAs. In the unknown-order blocks, there were 9 trials in each of 6 conditions (tone-first vs. letter-first x SOA). The sequence of trials was randomized independently for each block, and on each trial the letter and the tone were selected randomly and independently. The order of presentation of the 3 conditions was counterbalanced as follows. There were 3 groups of subjects, with the first performing the letter-first condition in Blocks 1, 4, and 7, the tone-first in Blocks 2, 5, and 8, and the unknown-order condition in Blocks 3, 6, and 9. The assignments for the other 2 groups were based on a rotation of this ordering.

Procedure. The subjects were given instructions in writing to describe the task. The instructions stated that the subject would make a button-push response to the tone and a button-push response to the letter. They were also informed that the order of the two stimuli would sometimes be fixed in a block, and would sometimes vary unpredictably from trial to trial. The instructions stated "your basic goal is just to make the correct responses to both the tone and the letter as quickly as possible. However, you should try to respond as promptly as possible to the *first* stimulus that appears, and then respond as promptly as possible to the second stimulus. Sometimes, you may be unsure of the order, or find yourself responding in the wrong order. This happens occasionally to everyone, so just try to respond as quickly as possible." Subjects began with 3 practice blocks of 30 trials, 1 block in each of the conditions just mentioned.

Each trial began with the presentation of a plus sign as a fixation point. The fixation point appeared at the center of the display for 1 s. It disappeared, and then the random foreperiod began. The duration of this foreperiod was determined in advance of each trial by starting with the base duration of 500 ms, and adding 30 ms in successive iterations until a random variable (probability of success = .9) failed. This guaranteed that the subject could not infer anything about when the stimulus would appear based on the amount of foreperiod that had elapsed so far (see Gottsdanker, 1986, for a discussion). After the foreperiod had elapsed, the first stimulus was presented, and after the appropriate SOA had elapsed, the second stimulus was presented. Subjects responded to the tone with their left hand, pressing the "z" and "x" keys for low and high tones, respectively. They responded to the letter with their right hand, pressing the "m," "," or "." keys for A, B, and C, respectively. If an error was made on either task, a warning message ("ERROR!") was displayed for 750 ms; beginning only after both responses were detected. The intertrial interval between completion of the second response and onset of the fixation point for the next trial was 1.3 s. At the end of each block, the subject rested until he or she felt ready to resume. During this period, feedback was provided for all preceding blocks consisting of mean correct RT for the tone task and number of errors on both the first and second task.

Results and Discussion

Basic results. The data collection produced 972 pairs of responses for each cell in the known-order blocks, and 486 pairs of responses for each cell in the unknown-order blocks. Any response times under 250 ms or in excess of 2,500 ms were discarded as deviant.

Figure 1 presents subjects' mean RTs for correct trials. The left panel presents tone responses as a function of condition (known vs. unknown order), order of stimuli (tone first vs. letter first), and SOA (100, 200, or 700 ms). The right panel presents the mean letter response RTs as a function of these same factors.

To begin with, an overall analysis of variance (ANOVA) was performed on these results, with factors being right versus left hand, first versus second response, known versus unknown order, and SOA. The results were as follows.

1. Naturally, the overall effect of SOA was significant, $F(2, 34) = 79.8$, $p < .001$. $MS_e = 16,049$, reflecting slower response times at shorter SOAs.

2. The slower responses resulting from unknown order—in Figure 1, the elevation of the dotted lines—averaged 218 ms, and was highly significant, $F(1, 17) = 85.8$, $p < .001$. $MS_e = 58,842$.

3. Looking only at the bottom two (solid) lines on the figures (pertaining to the known order conditions), one immediately notices a much greater dependence of RTs on SOA

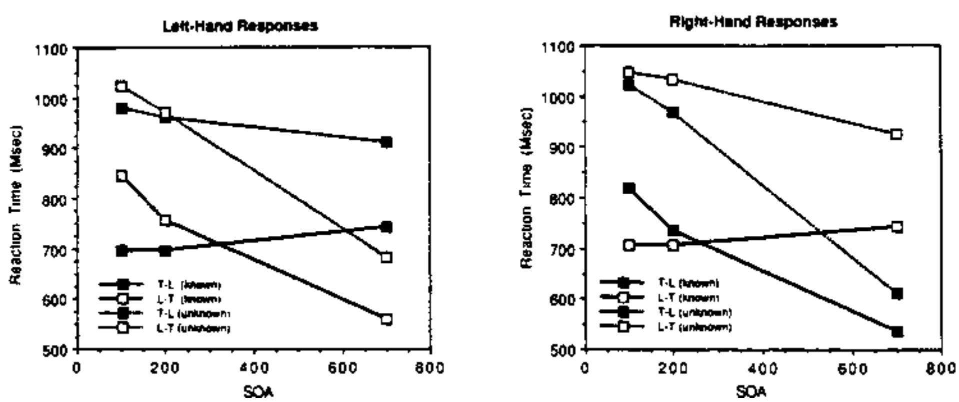

Figure 1. Mean response limes in Experiment 1. Left panel shows left-hand (tone) responses as a function of order of stimuli (T = tone, L = letter) and known versus unknown order. Right panel shows the same for right-hand (letter) responses.

for responses to the second stimulus presented rather than the first. The same is true of the top two (dotted) lines on each figure (the unknown-order conditions). The interaction of SOA and first versus second response was highly significant. $F(2, 34) = 90.6$, $p < .001$. $MS_e = 10{,}132$.

4. The cost of unknown order of stimuli is greater for the response to the first presented stimulus (262 ms) than for the response to the second presented stimulus (171 ms). The interaction of known versus unknown with first versus second response was significant. $F(1,17) = 91.8$, $p < .001$, MS_e = 2,415.

5. Overall, the tone and letter responses behaved very similarly. There was a minimal (3 ms) overall difference between the tone response and the letter response. There were only two interactions involving the hand that were significant. The first was an interaction with SOA, $F(2, 34) = 5.7$, $p < .01$, $MS_e = 2{,}342$. This reflects overall a steeper average slope for right-hand responses. The second interaction is a three-way interaction with known versus unknown order and SOA, $F(2, 34) = 7.2$, $p < .005$. $MS_e = 1{,}355$. This interaction basically reflects the fact that the steeper slopes in the right-hand responses appear only in the unknown-order condition.

6. The slopes were steeper overall in the unknown-order condition; thus, for the interaction of SOA and known versus unknown order, $F(2, 34) = 16.1$, $p < .001$, $MS_e = 10{,}582$.

7. The steeper slopes in the unknown-order condition are most evident for the second response: thus, the interaction of Known versus Unknown order x First versus Second order x SOA is significant, $F(2, 34) = 4.8$, $p < .029$, $MS_e = 1{,}384$.

Error rates. The mean error rates are presented in Table 1. The only significant results here were three main effects. The first was a higher error rate for unknown (3.4%) than known order (2.3%). $F(1, 17) = 10.9$, $p < .005$, $MS_e = 0.0011$. The second was a higher error rate for the right-hand response (3.4%) than for the tone response (2.2%). $F(1, 17) = 7.5$, $p < .02$, $MS_e = 0.0023$. Finally, there were more errors on the second response (4.2%) than on the first response (1.4%), $F(1, 17) = 21.8$, $p < .001$, $MS_e = 0.0039$. For the first response, the average error rates were 2.1 %, 1.2%, and 1.1%, for SOAs of 100, 200, and 700 ms. respectively. For the second response, the corresponding error rates were 3.9%. 4.4%, and 4.4%. respectively. The effect of SOA on error rates was not significant, and it did not interact with other variables. There is, therefore, no indication of substantial variation in the quality of processing achieved in the different conditions.

Table 1
Percent Errors in All Experiments

First stimulus-response	Known order	Unknown order
Experiment 1		
Tone-R1[a]	1.5	2.2
Tone-R2	4.2	5.9
Letter-R1	0.7	1.3
Letter-R2	2.9	4.0
Experiment 2: manual responses[b]		
Tone-R2	2.7	3.0
Letter-R1	2.0	3.2
Experiment 3		
Flash-R1	3.9	10.1
Flash-R2	12.6	8.7
Digit-R1	—	16.8
Digit-R2	—	18.9

[a] Percent errors as a function of order (known vs. unknown), which stimulus came first, and response. Thus, Letter-R1 refers to trials on which the letter came first and represents percent errors in response to the letters.
[b] Error rates for vocal responses are unavailable (see text).

Comments on the basic RT results. How can we summarize this rather lengthy set of results? Most of the results are quite straightforward. When subjects know the order of the two stimuli, the usual PRP function arises: The second response time is dramatically slowed with shortening of the SOA between the stimuli, whereas the first response is fairly independent of the SOA. When subjects do not know the order of two stimuli, a similar PRP function occurs. However, the unknown-order condition itself produces a dramatic (216 ms) slowing of responses.

Interestingly, this slowing affects the first response quite a bit more than the second response (Result 4). Why should this be? To understand this, it may be useful to think about the long (700 ms) SOA separately from the short (100 and 200 ms) SOA conditions. At the long SOA, the effect is easily explicable, because in the unknown-order condition, after the first stimulus has appeared, the subject plainly has enough time to infer which stimulus (S1 or S2) is coming next and prepare for it (whereas the identity of the first stimulus would not be so inferrable). More puzzling, though, is the observation that first responses are affected more by unknown order than second responses at the short SOAs as well. This is puzzling because, according to single-channel bottleneck models, in the short SOA conditions the second response is waiting on the completion of critical stages of processing in the first task (Pashler & Johnston, 1989; Smith, 1967). Thus, any slowing caused by not knowing which stimulus will appear first should propagate onto the second-task RT. Therefore, any slowing of the second task in the unknown-order condition should be at least as large as the slowing of the second task in that condition. This conclusion should hold even if the second task itself were to suffer no interference at all from the unknown order. Given the earlier results of Pashler and Johnston (1989), the most natural account pertains to the possibility of response grouping. When subjects do not know the order of stimuli, they may be more likely to couple the two responses: this would slow the first response much more than the second response. Some tentative hint that this may be going on was revealed in an informal examination of the distribution of interresponse intervals (IRIs), which indicated that for some subjects there was a profusion of very short IRIs in the unknown-order condition. There are not enough data points at any given SOA to support a full analysis of this possibility, and in any case, it would lead somewhat beyond the scope of this article. The main point here is simple enough: With two manual responses, not knowing the order of stimuli increases RTs very substantially.

Response-Time Dependency Analysis

Thus far, we have discussed the effect of different variables upon RTs for each of the two responses separately. Of course, the data actually consist of a bivariate distribution of R1 and R2 for each condition for each subject. There is potentially a great deal of information in this bivariate distribution relevant for the consideration of theory if it can be extracted and described in a comprehensible manner. This is not as easy as it might sound. Several writers have observed positive simple correlations between R1 and R2 times in PRP situations (e.g., Gottsdanker & Way, 1966; Pashler, 1984; Pashler & Johnston, 1989). These correlations reflect the degree to which the variance in one RT can be accounted for as a linear function of the other RT. However, they are highly sensitive to extreme values, and provide no information about how the relationship between the two responses might differ across the range of either R1.

How can this relationship be meaningfully described? The most obvious alternative is to examine mean R2 as a function of the absolute RT range into which R1 falls. Thus, one could make a plot on which a single data point would represent the mean RT for the second response for those trials on which the first RT fell between, say, 600 and 620 ms. Unfortunately, variation in the range of R1 times for different subjects would mean that the R1s in any particular bin would come from entirely different parts of the R1 distributions for different subjects. This, in turn, would make such an analysis perhaps even less informative than the overall correlation of R1 and R2.

To get around such problems, we adopt a different approach, which is somewhat akin to Vincentizing simultaneously on both RT distributions. The following analyses pertain only to the known-order blocks. In Figure 2 we plot the mean R2 time for responses paired to R1s in each decile of the R1 distribution, with decile on the x axis. The left panel refers to the tone second-task responses: the right panel refers to letter second-task responses. The analysis was conducted as follows. First, response pairs were eliminated in cases where response in the pair either fell outside the (200-2,500 ms) cutoffs or was incorrect. Then, for each subject, for each SOA, the R1s were ranked and assigned to deciles using linear interpolation where necessary. The mean latencies of the R2s corresponding to R1s in each of these bins were then computed. At this stage, then, for each subject there was a (potential) graph just like those in Figure 2, in which each data point (x, y) meant that y was the mean R2 time for those response pairs where the R1 times fell in that subject's xth decile of his or her R1 distribution for that particular SOA. To generate Figure 2, then, the y-axis values on these potential plots were simply averaged across subjects.

This procedure is rather complex, but the resulting graph answers a simple question that previous analyses have not addressed: How does the second RT depend upon where the corresponding R1 time lies in the R1 distribution? The figures provide a straightforward answer, which is the same for both letter and tone responses: At the shorter two SOAs, increase in the first RT over most of its range produces slowing of the second response. By contrast, at the longest (700 ms) SOA, the effect shows up only with the very slowest first responses. Note that linearity or the absence of it in the graphs is not informative, because moving from the xth to the (x+1)th decile of the R1 distribution would correspond to different absolute changes in R1 times for different values of x (and. to some degree, for different subjects). Therefore, even if each millisecond increase in R1 produced a corresponding millisecond increase in R2, one should not expect these curves to have any particular form without knowing the shape of the R1 distribution.

This analysis reveals a strong dependency of R2 upon the first response. With the short SOAs, this dependency is not confined to the longest R1s, but appears throughout much of the R1 distribution. This is compared to the case of separated response modalities in the next experiment.

Responding in a Reversed Abnormal Order?

One obvious question pertaining to the unknown-order condition is whether subjects sometimes respond in the opposite order to the appearance of the stimuli. To assess this, the number of trials in which subjects responded in the "abnormal" order were counted. On the trials in which the tone came first, the proportion of such trials were .155, .084,

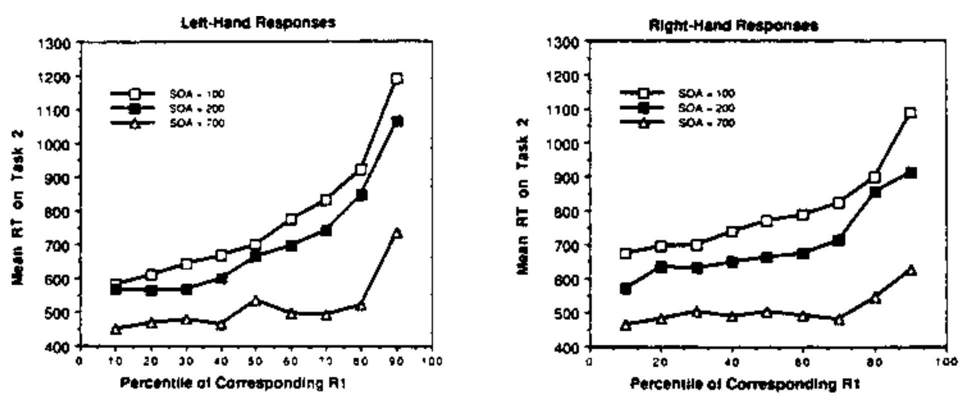

Figure2. Response-time (RT) contingencies in Experiment 1. Left panel shows mean left-hand second-task RTs as a function of percentile of corresponding R1. Right panel shows the same for right-hand second-task RTs.

and .033 for SOAs of 100, 200, and 700, respectively. For trials on which the letter came first, the proportion of such trials were .424, .306, and .034 for SOAs of 100, 200, and 700, respectively. Thus, as one might expect, there was a tendency for more abnormal responses at shorter SOAs; this effect was highly reliable. The less obvious effect—more abnormal response orders when the letter came first—was also highly reliable.

This concludes the examination of the effects of predictability of order and SOA in a dual-task situation with two manual responses. To summarize, the basic PRP effect appears very plainly in these data, and R2 times are strongly affected by R1 times but more so at short SOAs. These results fit postponement models (Pashler & Johnston, 1989) very well. However, an additional and very substantial slowing arises when the order of stimuli is not known to the subject in advance. Finally, subjects often respond in the "wrong" order, especially at the short SOAs.

Experiment 2: Manual/Vocal Responses

We turn now to an experiment that is very similar to Experiment 1, but provides response separation. This experiment differed from the first only in that the subjects responded to the tone vocally rather than manually. Subjects said "high" or "low" to the high and low tone, respectively. The other task still involved the three-choice manual response to a letter performed with the right hand.

Method

Subjects. Eighteen undergraduates at the University of California, San Diego, participated in the experiment in partial fulfillment of a course requirement. The data from 3 subjects were discarded because of technical malfunctions.

Apparatus and stimuli. The apparatus and stimuli were the same as in the previous experiment, except for the vocal responses. Subjects spoke through a DAK Industries ("auto-telescope") highly directional microphone, which was plugged into a Gerbrandts Model G1341T Voice-Activated Relay. The relay was in turn connected to the computer. The equipment was adjusted for each subject so that their vocal responses could be easily picked up without detecting key-presses. In addition, the entire session was audiotaped to allow some assessment of overall vocal error rates.

Design The design was exactly the same as Experiment 1.

Procedure. The procedure was the same as Experiment 1, except for the response to the tone. Subjects were warned to be accurate on both responses, and advised that the session would be recorded so that vocal errors could be detected. Feedback to the subject consisted of speed on both responses and accuracy of the button-push response.

Results and Discussion

Note first of all that the figures in this section are graphed on the same scale as the corresponding figures in Experiment 1 to allow easy comparison of the results of the two experiments.

Basic results. Any response times under 250 ms or in excess of 2,500 ms were discarded as deviant. Figure 3 presents subjects' mean RTs. The top panel pertains to vocal responses to the tone as a function of condition (known vs. unknown order), order of stimuli (tone first vs. letter first), and SOA (100, 200, or 700 ms). The bottom panel presents the mean RTs for correct right-hand responses to the letter as a function of these same factors.

To start, an overall ANOVA was performed on these results, with factors being right versus left hand, first versus second response, known versus unknown order, and SOA.

1. The overall effect of SOA was significant. $F(2, 28) = 27.0$. $p < .001$, $MS_e = 11{,}342$, reflecting slower overall response times at shorter SOAs.

2. The slower responses as a result of unknown order—Figure 3, the elevation of the dotted lines—averaged 72 ms. and was significant. $F(1, 14) = 17.6$. $p < .002$, $MS_e = 26{,}772$.

3. There was a much greater dependence of RTs on SOA for responses to the second stimulus presented rather than the first. Thus, the interaction of SOA and first versus second response was significant, $F(2, 28) = 34.8$, $p < .001$, $MS_e = 4{,}354$.

4. The cost of unknown order of stimuli was greater for the response to the first presented stimulus (121 ms) than for the response to the second presented stimulus (24 ms). The interaction of known versus unknown order with first versus second response was significant, $F(1, 14) = 80.8$. $p < .001$, $MS_e = 2{,}629$.

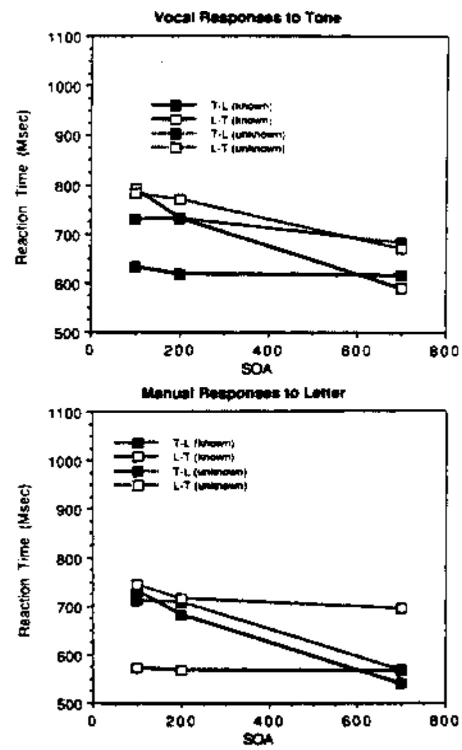

Figure 3. Mean response times (RTs) in Experiment 2. Top panel shows mean vocal (tone) responses as a function of order of stimuli (T = tone, L = letter) and known versus unknown order. Bottom panel shows the same for manual (letter) responses.

5. The vocal responses were an average of 46 ms slower than the manual responses, which was marginally significant, $F(1, 14) = 4.7, p < .05, MS_e = 39{,}550$. However, there were no significant interactions involving vocal versus manual responses.

Error rates. The mean error rates for the manual response are presented in Table 1. The only effect that approached significance was due to known versus unknown order (2.4% vs. 3.1% errors, respectively), $F(1, 14) = 3.77, .05 < p < .10, MS_e = .0007$. When the manual response came first, the error rates were 2.0%, 2.5%, and 3.4% for SOAs of 100, 200, and 700, respectively. When the manual response came second, the corresponding error rates were 3.0%, 2.8%, and 2.8%. The effect of SOA was not significant, nor were any interactions involving SOA. It was not feasible to record individual trial errors on the tone task. An audiotape was preserved for each subject, however, containing the tones and spoken responses. These were spot-checked to be sure that subjects were not committing an egregious number of errors. In fact, however, overall error rates appeared to be lower than for the comparable manual response in Experiment 1, probably because of the greater S-R compatibility of the response.[3]

Comments on the basic RT results. The most obvious difference between performance in the present task and performance with the two manual responses (Experiment 1) is the 67% reduction in the size of the effect of unknown order (72.3 ms vs. 216.2 ms). To assess the reliability of this effect, the overall means for known and unknown order conditions were compared across the two experiments, and the result was highly significant. $F(1, 31) = 22.9, p < .001$. Earlier in this article, it was hypothesized that the massive effects of modality observed in previous studies might have been due to the lack of predictable stimulus order. Indeed, the results make it clear that the effect of unpredictability of the order of two stimuli is much smaller with a vocal response and a manual response than with two manual responses.

Overall magnitude of interference. In the present experiment, using a manual/vocal response combination, reducing the SOA produces a significant second-task slowing when the stimuli appear in a predictable order: By definition, this is a PRP effect. This effect is sizable, and at least qualitatively consistent with underlying response selection postponement. The magnitude of this effect appears somewhat smaller than the effect in Experiment 1, using a manual/manual response combination, however. For present purposes, the main point is that previous research appears to have led to an obscuring of the PRP effect with separated responses, because it was compared with the case of two manual responses in experiments that used unknown stimulus order. It would be interesting, however, if some conclusions could be drawn here concerning the relative magnitude of the PRP effect as a function of response separation.

A precise comparison of this sort is ruled out by the fact that the vocal-response task (Experiment 2) and the manual-response task (Experiment 1) may differ in stimulus-response compatibility. It would seem likely that the classification of tones as "high" or "low" would be at least a bit easier than the more aribtrary selection of a button-push response. This difference by itself may well suffice to explain the differences between the two PRP effects. However, it may be useful to leave this aside and compare the two effects in more detail. When the (vocal) response to the tone came second (Experiment 2), the slowing of R2 as the SOA is shortened from 700 to 100 amounts to 202 ms. The comparable figure for the first experiment is 285 ms. When the (manual) response to the letter came second, the total SOA effect observed in Experiment 2 is 192 ms compared with 283 ms in Experiment 1. This comparison makes it clear that although there is very substantial SOA-dependent interference between tasks in both conditions, it is about one third smaller with the vocal/manual response combination of Experiment 2.

Before accepting the implication that response separation reduces the interference by even one third, however, it is necessary to examine RTs for the first response (R1) on the known-order trials. The effects of SOA on these R1 times were quite minimal in both experiments regardless of which response came first. This suggests that the "grouping" phenomenon discussed earlier in connection with the results of Pashler and Johnston (1989) is not playing much of a role here, and that we can safely average over SOA in examining the R1 times. Consider first the trials on which the tone came first. The tone response (R1) times average 712 ms and 623 ms in the first and second experiments, respectively. Consider the trials on which the letter comes first. The letter response (R1) times average 718 ms and 569 ms in the first and second experiments, respectively. This difference is significant, $F(1, 31) = 6.6. p < .02$. Note that in this case, we are comparing RTs to perform exactly the same task, when that task is performed immediately before another task, with the order known in advance. (This effect does not seem to be a quirk of the present two experiments; the author has recently observed another case of approximately 100 ms slowing of a particular first-task manual response when coupled with a manual as opposed to a vocal response.) Why should RTs be slower when the second task requires another manual response? This question brings us back to the earlier discussion of preparation effects in divided attention. When subjects have to maintain two mappings involving manual responses, the similarity may reduce the strength at which these links can be maintained, in the same way, perhaps, as item similarity can impair short-term memory performance (see Baddeley, 1966; also, Baddeley, 1976, for a review). This preparation account is quite testable, because it predicts that the slowing of one manual response produced by preparing another manual response should arise even if the performance of both tasks on the same trial is never required. Thus, one could examine single-task performance with no foreknowledge of which of the two tasks will occur on any given trial. Such experiments would be interesting in determining how modality is affecting R1 times here, but lead beyond our immediate concerns here.

[3] Therefore, the current analysis included all vocal responses, whereas the analysis of Experiment 1 included only the correct responses on the corresponding button-push task. An analysis of that data including these error trials showed, not surprisingly, that the exclusion of these trials made no difference to the significant findings of that experiment.

What is of immediate concern, though, is how our estimate of the magnitude of second-task interference should be affected by the observation that R1s are slower in the manual/ manual condition. From the point of view of the response selection postponement account, R2 slowing is timed to the point of completion of R1 response selection, which is in turn closely related to the first RT. Thus, we should adjust our estimate of R2 slowing accordingly. We can do this for the case where the tone came before the letter. In Experiment 1, at the 100-ms SOA, where postponement should occur virtually always, the mean R2 time is 820 ms, and the R1 time is 697 ms. In Experiment 2, on the other hand, the mean R2 time is 733 ms, or 87 ms faster. However, the mean R1 time is 633 ms, or 64 ms faster than in Experiment 1. In short, when the response modalities are separated, the second-task RT is indeed 87 ms faster than when the responses are both manual. However, these responses follow on the heels of a first-task response that is 64 ms faster. Thus, our final estimate of the effect of response separation on the mean amount of second-task slowing, timed from the first task, is a rather trivial 23 ms!

In summary, the data suggest that when the order is known, response separation does not attenuate interference at all, although it does facilitate preparation of either task. The arguments in the preceding section depend upon assumptions that one might debate, so the reader may prefer a more conservative conclusion. In that case, we can conclude that the interference with response separation is at least two thirds as large as the interference without response separation. Either way. the basic finding is clear: Response separation does not have dramatic effects with known stimulus order, but it does with unknown order.

Response-Time Dependency Analysis

It is suggested, then, that the interference with the second task observed in the manual/vocal task (Experiment 2), known order, is quantitatively about the same as that observed in the first experiment, which used two manual responses. The next question is whether this interference is the same in character. The first question here concerns the dependency between the two RTs. This information should be more powerful than the pattern of mean reaction times alone. If, as McLeod and Allport suggested, separate processors control performance of the two tasks, they might be subject to some nonspecific form of interference, resulting in a much weaker dependency between tasks than was observed in Experiment 1. In principle, this weaker dependency might be observed despite the fact that reducing the SOA increases second-task RTs, as discussed previously here. Suppose, for instance, that a single mechanism were required to initiate but not to complete response selection on both tasks: This could leave the RTs relatively uncorrelated, while producing SOA-dependent interference. To examine this issue, following the procedure of Experiment 1, Figure 4 plots the mean R2 time for responses paired to R1s in each decile of the R1 distribution, with decile on the x axis, examining data from known-order blocks only. The analysis was subject to the usual cutoffs for deviant trials.

Figure 4 shows that the response dependency has roughly the same character in this experiment as in the previous experiment: At the shorter two SOAs, variation in the first RT over its range produces a substantial slowing of the second response. By contrast, at the longest of the three SOAs, the effect shows up only with the slowest first RTs. These conclusions are just what one would expect from the response selection bottleneck account: Slowing of the second task arises when response selection for the second task must wait for completion of the corresponding stage of the first task.

Abnormal Order Responses

On the trials in which the letter came first, the proportion of trials on which an abnormal response order occurred were .321, .223, and .025 for SOAs of 100, 200, and 700, respectively. For trials on which the letter came first, the proportion of such trials were .377, .238, and .025 for SOAs of 100, 200, and 700, respectively. Thus, there is the obvious tendency for more abnormal order responses at shorter SOAs: this effect was highly reliable, as in the previous experiment. However, in this experiment, there was not much of the tendency to produce abnormal order errors more frequently when the tone came first.

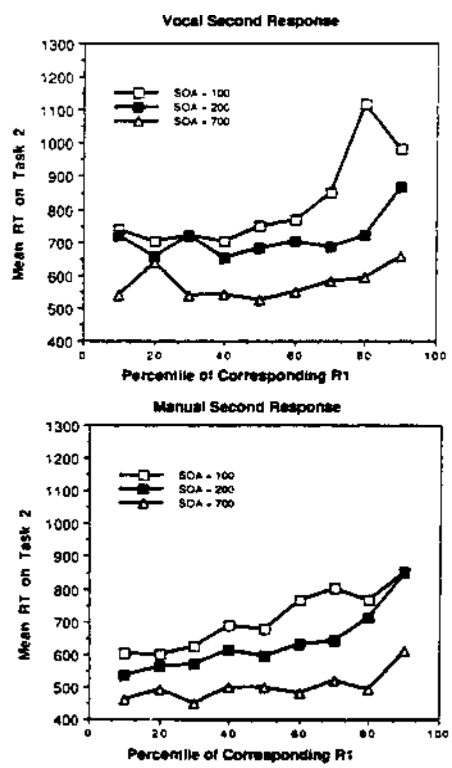

Figure 4. Response-time (RT) contingencies in Experiment 2. Top panel shows mean vocal second-task RTs as a function of percentile of corresponding R1. Bottom panel shows the same for manual second-task RTs.

Discussion of Experiments 1 and 2

The results of Experiments 1 and 2 make two important points. First, response separation does not eradicate dual-task interference in the PRP situation, nor does it much affect the dependency of RTs induced at short SOAs between stimuli. In fact, response separation may not even attenuate interference at all. Second, response separation interacts very dramatically with the predictability or unpredictability of the order of stimuli. It is very costly for subjects not to know in what order they must deal with stimuli when the responses are both manual. It is much less costly when there is one vocal response and one manual response. This finding may explain why previous results seemed to suggest that dual-task interference is a function of response similarity. When the order of stimuli is not known, a large extra measure of dual-task interference arises when two manual responses must be made. This is probably responsible for the dramatic effects of response separation in studies like those of McLeod (1978) and McLeod and Posner (1984).

What is causing the interaction of response separation and knowledge of the order of stimuli? One obvious possible explanation, noted earlier, is that the response execution stages of each task cannot overlap unless the two responses are separated. This could account for increased RTs, but cannot possibly account for the present results. First, why should it matter on this account whether the order of stimuli is predictable? Second, why should the first response be affected at all? Third, why do factors slowing response selection have effects that are additive with SOA and with single-task versus dual-task condition (Pashler, 1984; Pashler & Johnston, 1989)?

Another alternative is needed. The author informally observed, and several subjects spontaneously claimed, that the unknown-order condition was especially problematic because of a tendency for a certain type of error to intrude. These intrusions involved errors in which one hand made the response that was appropriate for the other hand. Thus, if the stimuli required a left-most finger response with the right hand, followed by a right-most finger response with the left hand, the left hand might act first, executing a left-most finger response. Such errors are henceforth referred to as spatially homologous response errors. The hypothesis suggested, then, is that the slowing in the unknown-order condition may reflect a strategy designed to prevent the intrusion of spatially homologous errors, an account that is sketched in more detail later. Plainly, if this is correct, it is important, because it would suggest that modality effects need an entirely different sort of account from the multiprocessor models suggested by McLeod and Allport. In the following experiment, this view is assessed by deliberately speed stressing the subjects and determining if a profusion of overt homologous errors can be observed.

Experiment 3

To determine if spatially homologous response errors occurred frequently in the unknown-order blocks, several changes were made. First, rather than using a two-alternative task and a three-alternative task, two three-alternative tasks were used to make the identification of spatially homologous responses more transparent. Second, fairly severe speed pressure was applied to the subjects to generate plenty of errors. Several other changes were made to assess the generality of the unknown-order effects observed in Experiment 1. First, the stimuli were both visual (one categorization was based on spatial position, the other on identity, and both were highly compatible mappings). Second, the random foreperiod used in Experiments 1 and 2 was replaced with a fixed foreperiod.

Method

Subjects. Twelve undergraduates at the University of California, San Diego, anticipated in the experiment, some for payment and some in partial fulfillment of a course requirement.

Apparatus and stimuli. The apparatus and stimulus were the same as in Experiment 1, except that both stimuli were visual. One stimulus was a pair of red rectangles, one slightly above and one slightly below the horizontal midline of the display. The squares were presented on the left, the middle, or the right of the display, with respect to the vertical midline, and the subjects responded with a left-hand compatible button-push response to this placement. Each of the red rectangles measured 0.6 cm wide x 0.3 cm high, and they were separated vertically by a distance of 0.8 cm. When the pair of rectangles was presented eccentrically, the horizontal distance from the center of the display to the squares was 2.0 cm. The second stimulus was a single digit, a 1, 2 or 3, also indicating a compatible right-hand button-push response. The digits measured about 0.3 cm wide x 0.4 cm high. The digit was always presented in the center of the screen. The separation between the rectangles and the digit did not appear to generate metacontrast masking.

Design. The experiment was divided into 12 blocks of 60 trials. Half of the blocks were known-order blocks, and half were unknown-order blocks. In the 6 known-order blocks, the red flash always appeared first. In the 6 unknown-order blocks, the red flash appeared in the first half of the time, and the digit appeared in the first half of the time. Three different SOAs (100, 200, and 700) were used equally often in the known-order blocks. Thus, each subject performed 6 blocks x 20 trials (or 120 trials) at each SOA in the known order. In the unknown-order blocks, the same three SOAs were used equally often in both orders. Thus, each subject performed 6 blocks x 10 trials, (or 60 trials) at each SOA in the unknown order. The stimuli were selected randomly and independently on each trial. The order of stimuli within a block was randomized independently for each subject. Subjects were divided into two groups. For one group the known-order blocks were Blocks 1-6, whereas for the other group the known-order blocks were Blocks 7-12. (Blocks of the same condition were kept contiguous to facilitate applying speed pressure; see the following.)

Procedure. The procedure was similar to that for Experiment 1. However, subjects were strongly pressured to make rapid responses. Written instructions stated that the experimenters wanted the subjects to "respond VERY RAPIDLY," and added that "naturally, this means you will make quite a few errors." During the rest periods between blocks, feedback was provided, which consisted of speed on both responses and number of errors. If the proportion of errors on the preceding block was less than 10%, subjects were warned by the computer to try to respond more rapidly, and if error rates exceeded 40%, they were warned to respond more accurately. The trial began with a fixation point in the center of the screen for 1 s, followed by a fixed 800-ms foreperiod, and then the first stimulus appeared. The red flashes remained on the screen for 100 ms, and the digits remained for 400 ms. Subjects began with 2 blocks of 18 practice trials, 1 block in each order condition. Subjects responded to the red flashes by pressing the "z," "x," or "c" keys on the microcomputer keyboard with their left hand, in response to left, central, or right positioning of the red flashes, respectively. They responded to the digits by pressing "m," "," or "." keys in response to the digits 1, 2, or 3, respectively. Subjects used the first three fingers on each hand for their responses, and they kept these fingers rested on these keys throughout.

Results and Discussion

Basic Results. Any RTs under 250 ms or in excess of 2,500 ms were discarded as deviant.

Figure 5 presents subjects' mean correct RTs. The top panel shows the known-order condition, as a function of response (left vs. right hand), and SOA (100, 200, or 700 ms). The middle panel presents the mean RTs for the unknown-order trials where the flashes precede the digits as a function of order, response, and SOA. The bottom panel presents the corresponding data for unknown-order trials where the digits precede the flashes.

Several different analyses were performed on the data. First, an ANOVA was performed to compare the left-hand responses in the known-order condition (where the flashes always come first) with the left-hand responses in the unknown-order condition, considering only one half of the trials—those in which the left-hand (flashes) stimuli came first. This included two factors: known versus unknown order and SOA. The unknown-order condition was slower (680 ms versus 478 ms), which was significant. $F(1, 11) = 96.1$. $p < .001$, $MS_e = 7,628$. The effect of SOA was not significant. $F(2, 22) = 0.89, p > .40$. The interaction was not significant.

A similar analysis was performed on the right-hand responses comparing the known-order condition with the comparable trials from the unknown-order condition (those in which the digit came second, as it always did in the known-order condition). The unknown-order condition was slower (648 ms vs. 519 ms). which was significant, $F(1, 11) = 19.4, p < .001$, $MS_e = 15,274$. The effect of SOA was significant. $F(2, 22) = 74.8, p < .001$, $MS_e = 4.065$. The interaction of Order x SOA was also significant, $F(2, 22) = 4.9, p < .02$. $MS_e = 2,148$. This seems primarily to reflect a larger effect of SOA in the unknown-order condition.

In summary, then, the results show an ordinary PRP function—greater slowing of the second response as SOA is shortened—for both known- and unknown-order conditions. The first response is not much affected by SOA in either condition. As in the previous experiment, responses are much slower when the order of the stimuli is unknown. This indicates that the results of Experiment 1 do not at all depend upon having a randomly varying foreperiod, nor do they depend upon having a visual and an auditory stimulus.

Error patterns. The focus of the present experiment was upon using speed stress to generate plenty of errors to examine the pattern of these errors. The mean error rates for the manual response are presented in Table 1. Plainly, the overall mean error rate (8.9%) is much higher than in the first experiment (1.9%), as hoped.

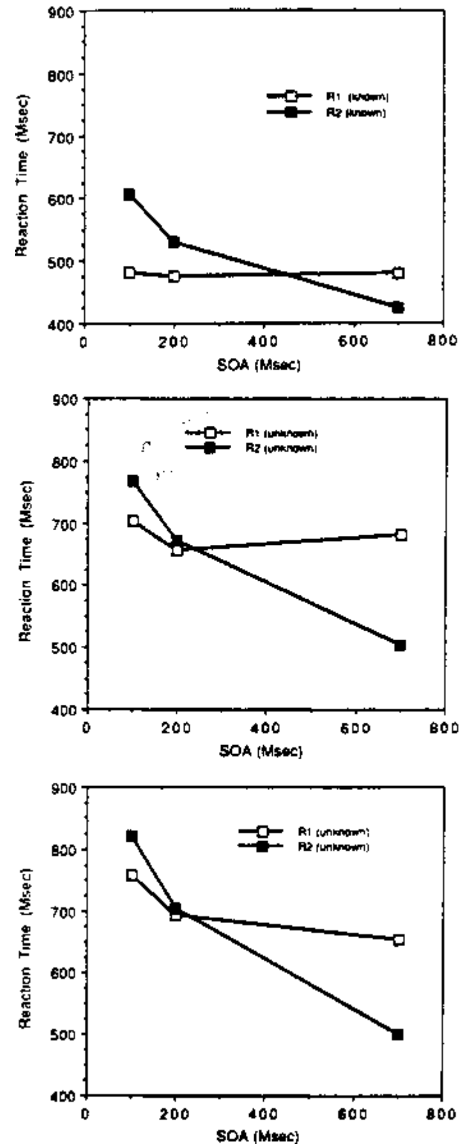

Figure 5. Mean response-times in Experiment 3. Top panel shows known-order condition (R1 = first response. R2 = second response). Middle panel shows the same for unknown-order condition, trials where flashes precede digit. Bottom panel shows the same for unknown-order condition, trials where digit precedes flashes.

The key question is whether subjects make a disproportionate number of errors that consist of making the appropriate response (e.g., left-most finger) on the wrong hand, that is, spatially homologous response errors. What is the appropriate way to count such errors? Consider any given trial on which an error is made with, say, the right hand. If the stimulus on the left hand requires a response that is spatially homologous to the correct response, then obviously the right-hand response could not be a homologous response error. Homologous right-hand response errors can be noted only when the left-hand stimulus requires a response that is homologous to something other than the correct response for the right hand.

Thus, we start by restricting the analysis to trials on which an error is made on a given hand, and the other stimulus requires a response not homologous to the correct response on the hand that made the error. Having made this restriction, all we have to do is ask whether the number of error responses that are homologous to the response indicated by the other stimulus is greater than the number of error responses that are not so homologous. Because these are three-choice tasks, the number should be equal by chance, averaged over response positions.

Figure 6 presents the data broken down as a function of order (known vs. unknown) and what the response should have been (left vs. middle vs. right). The figure shows a disproportionate number of homologous errors compared with nonhomologous errors, and also that this disproportion is much more extreme for the unknown-order condition. To assess significance, an ANOVA was performed with number of trials as the dependent variable. A four-factor ANOVA involved the following variables: order (known vs. unknown), response hand of error (left vs. right), what the response should have been (left vs. middle vs. right), and type of response (homologous error vs. nonhomologous error). There were more errors in the unknown-order blocks than in the known-order blocks (6.4 vs. 3.1), $F(1, 11) = 26.8$, $p < .001$, $MS_e = 29.1$. There were more homologous errors than nonhomologous errors (7.4 vs. 2.2). $F(1, 11) = 46.4$, $p < .001$, $MS_e = 42.3$. The effect of homologous versus nonhomologous interacted with known versus unknown order, $F(1, 11) = 25.5$, $p < .001$ $MS_e = 17.6$. This reflects the fact that in the known-order condition, homologous errors outnumber nonhomologous errors (4.5 vs. 1.8), but not nearly as much as in the unknown-order condition (10.3 vs. 2.6). This interaction speaks directly to the basic hypothesis of the experiment.

There were several other significant effects, however. There were more errors on the right hand than on the left hand, $F(1, 11) = 5.6$, $p < .05$, $MS_e = 15.1$. This interacted with known versus unknown order, $F(1, 11) = 13.5$, $p < .005$, $MS_e = 19.6$. This interaction probably reflects the fact that there are more errors on the second response in the known-order condition: in the unknown-order condition, the left and right responses do not correspond to first and second responses, as they do in the known-order condition. The effect of correct response position (left vs. middle vs. right) was significant, $F(2, 22) = 12.6$, $p < .001$, $MS_e = 7.2$. This interacted with known versus unknown order, $F(2, 22) = 5.3$, $p < .02$, $MS_e = 3.8$. and with left versus right response, $F(2, 22) = 6.0$, $p < .01$, $MS_e = 7.7$. Finally, there was a three-way interaction between Left versus Right x Response Position x Homologous versus Nonhomologous, $F(2, 22) = 4.7$, $p < .03$, $MS_e = 5.1$. The source of this interaction was not clear to the author. The hypothesis under consideration suggests that there might be more spatially homologous errors at short SOAs. To assess this, for each Subject x SOA x Known- versus Unknown-Order cell, the proportion of the total errors that were spatially homologous was computed. (This collapsed over all the other variables to make sure that there were some errors in each cell; otherwise, the proportion would be undefined.) If there was no tendency for the errors to be homologous, then the expected value of this proportion would be .5. The overall average was .68. higher for the unknown order (.76) than the known order (.60). The effect of block type was significant, $F(1, 11) = 6.0$, $p < .04$. $MS_e = 0.069$. The proportion decreased as SOA was lengthened (.74, .70, and .61 for SOAs of 100, 200, and 700, respectively). The effect of SOA was significant, $F(2, 22) = 4.2$, $p < .03$, $MS_e = 0.026$. The interaction of the two was not significant.

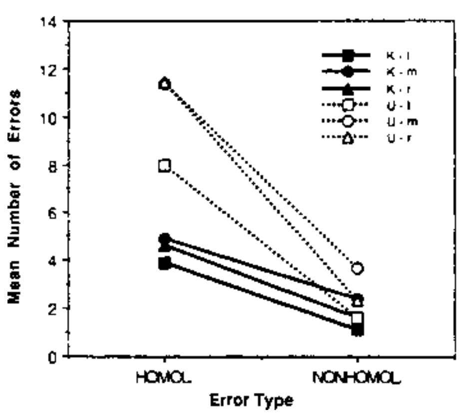

Figure 6. Experiment 3: error types. Mean number of homologous and nonhomologous errors in each cell (see text) as a function of known versus unknown order and position where the response should have been. K = known order; U = unknown order; l = left position; m = middle position; r = right position.

Conclusions

The results of this study support the supposition that the unknown-order condition produces a large increase in spatially homologous response errors. The results suggest, then, that the overall slowing observed in the unknown condition reflects a strategy that is mobilized to avoid proliferation of these homologous errors.

What might be causing these errors, and why exactly should they occur so much more frequently in the unknown-order condition? Assume that the process of selecting a response is subject to single-channel queuing (Pashler, 1984, 1989). Suppose that the response selection mechanism selects not the button to be pushed, but rather the direction of desired movement or a trajectory in space. To generate a response, further features must be specified, including which particular effector is to be used or the location of the exact trajectory to be followed. One may think of this last process as involving the setting of a "switch" specifying the effector to be used. Suppose further that given the appropriate intention, this switch is rapidly and easily switched from one setting to another. In the known-order condition, then, the switch is rested at one setting, and as soon as the first response has been made it is switched to the other position. Sluggishness in the switching will generate homologous errors (which should of course occur more frequently for the second response than for the first). The unknown-order condition is more problematic, however. Now the switch setting can be determined only as a function of the nature of the stimulus itself. For example, instead of simply storing a mapping from the left, middle, and right red flashes onto the left, middle, and right directions (in Experiment 2), a mapping must be stored that specifies the correct switch setting as well. Presumably, in both Experiments 1 and 3, this partly throws away whatever advantage is to be derived from the favorable S-R compatibility.

These conjectures cannot readily be further tested within the dual-task paradigm used here, but various other designs, including transfer of learning designs, could be used. If they are correct, then one would expect that practice with a particular S-R mapping would show quite good transfer when the same responses are effected with different effectors. (Consider the case of an experienced typist induced to switch from habitual five-fingered typing to one-fingered typing: Speed deteriorates, but performance does not break down as it would, say, on transfer to a new keyboard arrangement.) Transfer from one hand to another should also be reasonably efficient on this conception. Now what of the response separation case (Experiment 2)? Why does unknown stimulus order have a much smaller cost when one response is vocal and the other manual? On this account, the answer is plain enough: The manual effector switch can be kept at a single setting throughout. In summary, the results of Experiment 3 show that homologous response errors are indeed increased by lack of knowledge about the order of stimuli, and these results can be accounted for by proposing that manual response selection involves a hierarchical arrangement of decisions; when the order of stimuli is known, one of these decisions can be harnessed to temporal order rather than stimulus identity.

General Discussion

The present article began with a consideration of how using different response modalities may modulate dual-task interference. Previous writers have asserted that such interference is eradicated or dramatically reduced by using very different modalities, and furthermore that this eradication rules out central bottleneck accounts of divided attention in simple tasks. A literature review showed that the previous results did not actually demonstrate eradication of interference, except in possibly degenerate cases (e.g., where preview was allowed, where one or both of the tasks involved did not require response selection contingent on stimuli, where one task was not speeded, and so on). The review also raised the hint that the most pronounced effects of response separation might arise when the order of stimuli is not known to the subject. Previous workers have sometimes used known order, and more commonly an unknown order, but never apparently manipulated or discussed this potentially important factor. The present work was intended to accomplish two primary purposes. The first was to see whether response separation would eradicate interference in cases carefully designed to be nondegenerate, in the sense described previously. The second was to examine the effects of predictability of the order of stimuli, and to see whether this factor interacts with response separation in the suspected way.

The results suggest that response separation effects are largely, if not entirely, products of the suspected interaction with knowledge of order. The final experiment also suggests a likely cause for the interaction discovered here. To review, the four main results of the present work were as follows.

1. When subjects do not know the order in which two simple dual-task stimuli will arrive, this produces about three times as much disruption in the case of two manual responses as it does in the case of a manual and a vocal response (measuring disruption in latency increases).

2. Response separation is of modest benefit to performance of the first task with the known stimulus order and even at the longest SOA, suggesting an effect upon preparation for the tasks.

3. In the known-order condition, once the preparation factor noted in the second result is taken into account, response separation does not appear to attenuate the interference caused by proximity of the other task. This interference is manifested in (a) a slowing of responses with shorter SOAs and (b) a positive dependency between RTs on the two tasks.

4. When two manual responses must be performed, subjects' failure to know the order of stimuli produces an increase in the incidence of spatially homologous response errors, where one hand makes the response that would have been appropriate to the other hand.

These results confirm suggestions by previous workers that dual-task interference can be powerfully modulated by response similarity. However, they do not support previous accounts of this modulation. If multiprocessor models were correct, response separation should be sufficient to eradicate interference regardless of whether the subject knows the order of stimuli or not. The pattern of results that did arise is in fact consistent with the existence of a bottleneck at response selection, although of course they do not specifically demonstrate that (on that point, see Pashler, 1984, 1989, Pashler & Johnston, 1989). We can account for the present results by supposing that on top of a response selection queuing (which occurs regardless of response separation), an additional response-programming-related factor retards production of two manual responses with unknown order.

This analysis of response separation effects is quite different from that proposed by earlier workers. It was generally surmised that the extra difficulty caused by overlapping response modality must be because the execution of the two tasks requires a single mechanism when the two tasks are similar. However, Result 2 suggests that, with known stimulus order, response similarity has primary effects not on the execution of any particular aspects of the task, but rather on the mental preparation of the appropriate mapping. Result 1 indicates that a seemingly unimportant aspect of the paradigms reviewed in the introduction—that the subject cannot tell which task will have to be dealt with next—is essential for obtaining dramatic response separation effects. And Result 4 suggests an account for this, in terms of mechanisms of response programming. It is not claimed here that the results reported here, by themselves, demand a single-channel bottleneck interpretation. Rather, these findings indicate that effects of response separation do not behave as predicted by the multiprocessor models, and appear consistent with a (suitably amended) single-channel model for which there is now substantial independent support.

General Implications

The results discussed so far have several interesting implications, practical as well as theoretical. When unpredictable stimulus arrival is unavoidable, as it probably is in most applied fields such as aviation, then rapid accurate responses can be imperiled if the same modality is used. Conversely, if response modalities must be the same, then unpredictability of stimulus presentation should be avoided if the penalty for response delay or errors is high. This does not reflect a general principle of attentional allocation. It is specific to situations where rapid responses are required. Using brief displays, Pashler and Badgio (1987; Badgio & Pashler, 1988) found that predictability of the order of visual stimulus onset does not have a measurable effect upon accuracy of responses made at leisure, even when the display load is so severe that capacity limits are evident by the well-known criterion of Shiffrin and Gardner (1972). In short, the implication for interface design is that unpredictability of stimulus arrival is very troublesome when similar modality responses must be made, mildly troublesome when dissimilar responses must be made, and without any apparent effects at all when a complex perceptual judgment must be made upon two visual displays.

At a theoretical level, the conclusions reached here are consistent with the conclusion that the single-channel bottleneck may represent as ubiquitous and fundamental a characteristic of human mental processes as Welford (1952) and his colleagues originally surmised. The "disproof of the single-channel hypothesis" announced by Allport et al. (1972) appears to have been premature. However, the results also point to the fact that as experimental situations become more complex additional sources of interference may arise on top of this central interference. Perhaps under certain circumstances they can even dwarf the central interference. The difficulty in dealing with unknown-order stimuli with multiple manual responses is one example of such a factor. However, it seems likely that still more complex interactions can be generated as more complex tasks are studied carefully. Such interactions may be occurring in the studies recently reported by Hirst and Kalmar (1987) and Navon and Miller (1987). These authors concluded that dual-task interference was severely exacerbated when the cognitive components of the tasks combined were very similar or when the outcomes on the respective tasks could potentially generate cross-talk. Thus, Hirst and Kalmar required subjects to detect errors in spoken sequences of digits or letters, with each of two sequences presented continuously to an ear at one item per second. Subjects had much more trouble following two arithmetic sequences than following one arithmetic sequence and one letter sequence. The authors pointed out that results of this type are problematic for multiple resource theories, because within that framework, one would have to posit new resources to account for each new case of differential interference. They suggest that an entirely new kind of model will be needed.

However, results of this kind are not problematic for the approach discussed here, which postulates a fundamental single-channel limitation with other factors sometimes superimposed on top of it. Hirst and Kalmar's subjects had to retain multiple stimuli over periods of several seconds. Therefore, it is inevitable that any factor known to adversely affect short-term memory would also affect performance in this context. Interitem similarity has powerful adverse effects on short-term memory (see Baddeley, 1966, 1976), so it is hardly surprising that these appear in Hirst and Kalmar's tasks as well. Such research does not provide any indication of which processes are actually occurring at the same time and which are operating sequentially. Thus, the performance studied by Hirst and Kalmar may have depended upon serial execution of many elementary mental processes, spread out over the many seconds consumed by a "single trial." The ultimate success of the total assemblage of these many elementary mental acts may have depended upon the sufficiency of short-term memory to bridge the temporal gaps inserted by this switching. For this reason, then, task-similarity effects observed may have little to do with the basic dual-task limitations observed in PRP tasks. Nonetheless, many situations that are referred to in ordinary life as "doing two things at once" may have exactly this character, and the work of Hirst and Kalmar is useful in calling attention to a variable that can have powerful effects on performance. By contrast, the present approach examines dual-task performance in real time, starting with the most elementary forms of interference, and aims to understand progressively more complex situations in terms of these elementary limitations. The results thus far are revealing a fundamental bottleneck in response selection (and also a wholly independent perceptual limitation that arises with sufficiently complex stimuli; on this, see Pashler, 1989).

References

Allport, D. A. (1979). Attention and performance. In G. Claxton (Ed.), *New directions in cognitive psychology* (pp. 112-153). London: Routledge & Kegan Paul.

Allport, D. A., Antonis, B., & Reynolds, P. (1972). On the division of attention: A disproof of the single-channel hypothesis. *Quarterly Journal of Experimental Psychology, 24,* 225-235.

Baddeley, A. D. (1966). Short-term memory for word sequences as a function of acoustic, semantic and formal similarity. *Quarterly Journal of Experimental Psychology, 18,* 362-365.

Baddeley, A. D. (1976). *The psychology of memory.* New York: Basic Books.

Badgio, P. C.& Pashler, H. E. (1988). *What is the nature of capacity limitations in visual object recognition!* Manuscript submitted for publication.

Broadbent, D. E. (1982). Task combination and the selective intake of information. *Acta Psychologica, 50,* 253-290.

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.

Gottsdanker, R. (1986). Studying reaction time with nonaging intervals: An effective procedure. *Behavior Research Methods, Instruments, and Computers, 18,* 287-292.

Gottsdanker, R., & Way, T. C. (1966). Varied and constant intersignal intervals in psychological refractoriness. *Journal of Experi-*

mental Psychology, 72, 792-804.

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

Hirst, W. (1986). The psychology of attention. In J. LeDoux & W. Hirst (Eds.), *Mind and brain: Dialogues in cognitive neuroscience* (pp. 105-141). New York: Cambridge University Press.

Hirst, W., & Kalmar, D. (1987). Characterizing attentional resources. *Journal of Experimental Psychology: General, 116,* 68-81.

Kahneman, D. (1973). *Attention and effort.* New York: Prentice-Hall.

Keele, S. W. (1973). *Attention and human performance.* Pacific Palisades. CA: Goodyear.

Logan, G. (1978). Attention in character classification tasks: Evidence for the automaticity of component stages. *Journal of Experimental Psychology: General, 107,* 32-63.

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

McLeod, P. (1978). Does probe RT measure central processing demand? *Quarterly Journal of Experimental Psychology, 30,* 83-89.

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

McRuer, D. T., & Jex, H. R. (1967). A review of quasilinear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8,* 231-249.

Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 435-448.

Norman, D. A., & Shallice, T. (1985). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.). *Consciousness and self-regulation* (Vol. 4). New York: Plenum Press.

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., & Badgio, P. (1987). Attentional issues in the identification of alphanumeric characters. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance XII: The psychology of reading* (pp. 63-81). Hillsdale. NJ: Erlbaum.

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

Posner, M., & Boies, S. J. (1971). Components of attention. *Psychological Review, 78,* 391-408.

Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a Stroop task. *Journal of Mathematical Psychology, 18,* 105-139.

Shiffrin, R. M., & Gardner, G. T. (1972). Visual processing capacity and attentional control. *Journal of Experimental Psychology, 93,* 72-83.

Smith, M. C. (1967). Theories of the psychological refractory period. *Psychological Bulletin,* 67, 202-213.

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.

Welford. A. T. (1980). The single-channel hypothesis. In A. T. Welford (Ed.). *Reaction time* (pp. 215-252). New York: Academic.

Wickens, C. D. (1976). The effect of divided attention on information processing in manual tracking. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 1-13.

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