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Processing Stages in Overlapping Tasks: Evidence for a Central Bottleneck

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This article examines the attentional limits responsible for task slowing in the overlapping task (refractory period) paradigm. Five experiments are reported in which stimulus factors were manipulated in visual search tasks performed in isolation or temporally overlapping with another task. Bottleneck models suggest that second-task slowing is caused by postponement of "attention-demanding" stages of the second task, while earlier "automatic" stages proceed unhindered. A prediction was derived from this class of models, namely that in the overlapping task condition the effect of second task factors that slow automatic stages should be reduced, whereas the effect of factors slowing later nonautomatic stages should be unchanged. The data (Experiments 1-4) exhibit such a pattern and suggest that encoding and comparison stages of the second task, but not response selection, occur in parallel with work on the first task. The absence of overadditive interactions in these experiments, and also the effects of manipulating first-task factors in Experiment 5, seems to argue against capacity sharing as the source of the slowing in this task combination. Some implications of these results for attention theory are discussed.

The study of divided attention is directed toward characterizing the limits on simultaneous cognitive processes. A great deal of recent research in this area has examined the degree to which simultaneous perceptual processing of multiple stimuli is possible. The present investigation examines a closely related question: When a subject attempts to perform two simultaneous *tasks,* each requiring a separate response, what kinds of interference occur? What is at issue, therefore, is division of attention between different stimulus-response processes, rather than different stimuli requiring a single response. Interference among such separate processes occurs reliably (e.g., Vince, 1948), but its nature has not been generally agreed upon.

Dual-task studies have been performed using a number of different paradigms. In this article, the emphasis will be on the *overlapping tasks* paradigm (often called the *psychological refractory period paradigm;* for reviews, see Bertelson, 1966; Kantowitz, 1974). In this paradigm, subjects make a separate response to each of two stimuli (S1 and S2). The corresponding responses—R1 and R2—are made in the same order as the stimuli are presented. The stimuli occur in close succession, and S2 is generally presented prior to the occurrence of R1. Interference appears in a characteristic slowing of both responses—henceforth, *R1 slowing* and *R2 slowing*—compared to the corresponding latencies when the same tasks are performed alone.

A number of general approaches to divided attention have been proposed. One class of theories proposes that there are certain stages of processing (constituting a bottleneck) that cannot be performed simultaneously on more than one input. It is sometimes said that they require a "central processor" (Posner, 1978) or a "single channel" (Welford, 1981). The analyses most often proposed specifically to account for R2 slowing in the overlapping tasks paradigm fall into this class of *bottleneck models.* These models suggest that R2 slowing

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occurs because the stages of each task that involve the bottleneck must be performed in sequence; they differ on where the alleged bottleneck occurs. However, there is another broad class of models, more recent in origin, that has been proposed to account for a variety of dual-task phenomena. These models propose that various cognitive operations draw on limited resources. Some capacity theorists have suggested that there is a single resource pool that is used for all cognitive operations (Kahneman, 1973); others have argued for multiple resources used in different cognitive operations (e.g., Wickens, 1980). The central idea is that the various mental operations may be scheduled to operate concurrently; however, the speed and accuracy of their operation will be limited by the quantity of resources they are allocated. This kind of model permits various different processing strategies to be adopted, including sequential processing or switching; where it differs from the bottleneck views is in claiming that, in principle, a wide variety of different cognitive operations *may* operate in parallel, with resource scarcity causing a graded reduction in performance. McLeod (1977b) has shown that general capacity sharing might account for the major phenomena of the overlapping task paradigm, on the assumption that all of the work of both tasks is performed simultaneously. In this article, the behavior of a particular task combination is studied in an effort to see whether any particular stages are actually operating as a bottleneck model suggests or, alternatively, whether these stages are operating in a resource-depleted fashion. Naturally, evidence for a bottleneck in some particular pair of tasks is not evidence against the entire capacity-sharing perspective, because that perspective grants that sequential processing is a possible strategy.

The present research makes use of an analysis in terms of processing stages (Sternberg, 1969a; Sanders, 1980) to try to locate the source of the interference that occurs when two tasks are combined in the overlapping tasks paradigm: to determine if there is a bottleneck in a particular task combination, and if so, where it is located. The remainder of the introduction is divided into three sections. (a) The first briefly discusses some of the models that have been proposed to account for overlapping task data, (b) The second presents a framework for describing ways in which different stages of different tasks could interfere with each other and describes a way in which types of interference can be diagnosed by making comparisons of factor effects in and out of the overlapping task condition, (c) The third briefly discusses the relationship between the present approach and some previous relevant work.

Models of Overlapping Tasks

A range of bottleneck models of dual tasks has been discussed over the years. The first of these locates the bottleneck in the perceptual process itself: This is the *perceptual postponement model.* One kind of observation widely-believed to argue against a perceptual bottleneck involves effects of unattended visual material (e.g., Stroop, 1935; Shaffer & LaBerge, 1979) that suggest unattended material is often perceived automatically, that is, involuntarily and without interference (but see Broadbent, 1982, for another interpretation). Also, stimulus encoding may not be accompanied by elevation in simple reaction time (RT) to a concurrent auditory probe (Posner & Boies, 1971). Furthermore, the sheer magnitude of R2 slowing (sometimes several hundred ms) argues that limits on perceiving successful stimuli cannot be *solely* responsible.

A more promising interpretation locates the source of R2 slowing primarily in decision or response selection stages. Work in a variety of divided attention paradigms has led to formulations sharing this general perspective. For instance, Ostry, Moray, and Marks (1976) found that subjects can monitor stimuli coming into both ears effectively so long as they do not detect a signal in both ears at the same time. Subjects' ability to detect a signal in one ear is greatly reduced if there is a target in an other, or if they falsely think that there is. Performance in visual monitoring tasks is very similar: Subjects can monitor two channels about as effectively as one unless there is a signal in both (Duncan, 1980). Duncan has shown that the performance decrement with two-target trials is not attributable to the requirement to execute two responses: If the task is simply to decide whether one or two targets are present, sensitivity is significantly reduced when there are two. Duncan suggests that all stimuli are automatically identified in parallel but must be transferred to a more durable (and possibly conscious) system before they can support a response. Both the transfer mechanism and the subsequent storage mechanism are held to be severely limited in capacity. On this account, divided attention tasks show interference effects only when they impose extra demands upon these mechanisms, such as when more than one target is simultaneously detected.

Duncan does not specifically apply his theory to overlapping tasks, but others have made suggestions along these lines. Concentrating on the overlapping task paradigm, M. Smith (1967) and Welford (1952; 1981) use somewhat different terminology, but suggest basically the same thing: The processes intervening between the perceptual analysis and the execution of a response are unable to handle more than one task at a time. The term *decision postponement model* will be used henceforth to refer to the claim that R2 slowing results from a bottleneck in decision and/or response selection processes.

The third bottleneck model that might characterize the limitations seen in this paradigm is proposed by Keele (1973; Keele & Neill, 1978). This model, the *response-initiation postponement model,* proposes that the bottleneck in the performance of simultaneous tasks is at the point of initiation of distinct responses. The second-task slowing is assumed to reflect a postponement of the second response initiation due to having just executed the first response. Stages prior to response initiation are claimed to proceed without attention. As M. Smith (1967) points out, interference caused by R1 clearly cannot be the entire source of the R2 slowing, because that may be observed even when no response is required to the first stimulus (Nickerson, 1965; Kay & Weiss, 1961). On the other hand, this slowing is much smaller than the slowing observed in the ordinary two-response paradigm, so response postponement *might* be a very significant factor. Capacity sharing models of overlapping tasks will be discussed later in the introduction.

It should be emphasized that one cannot assume that there will be any correct general theory applicable to all overlapping tasks. For instance, it has been suggested that task combinations involving two manual responses may produce interference that is absent when the responses are of different modality. McLeod (1977a) has provided evidence that is suggestive of this possibility; related proposals have been made by Greenwald and Shulman (1973) and Allport, Antonis, and Reynolds (1972). In addition, different models might characterize performance of the same task after different degrees of practice. Nonetheless, the existing evidence does not even seem to be capable of ruling out any of these models for a given task combination. I will suggest later that this is true because the factors that have typically been manipulated in overlapping task paradigms—especially "task difficulty" and interstimulus interval (ISI)—are likely, upon any reasonable model, to have a large number of different effects.

Analytic Method

For the purposes of the exposition, I will begin by assuming an unrealistically simple stage model of the two tasks in an overlapping task paradigm. This will make it possible to describe most clearly the kind of reasoning that will be employed here. Then, in the discussion of some of the experiments, the consequences of weakening some of these assumptions will be examined. We will start by assuming that performance of a task can be decomposed into a set of successive stages in real time, each stage logically contingent upon the preceding. For the purposes of the present discussion, we will consider the hypothetical case in which the duration of the stages does not vary from trial to trial; later, it will be observed that the predictions do not qualitatively change when the durations are assumed to be variable.

Several terms must be defined before proceeding. In what follows, I will refer to *postponing* a stage to mean the following: making it impossible for that stage to begin until a certain point in time, without regard to whether the preceding stages are complete before that time, but *permitting* the earlier stages to proceed. Thus, performing a first task would postpone a stage in a second task if that stage simply could not begin until some point had been reached in the processing of the first task, or until some period of time after the completion of the first task had elapsed, even though the results of the previous stages in the second task might already be available. A defining feature of postponement, as the term is used here, is that the postponed stage cannot begin until a point in time that is delayed arbitrarily with respect to progress on preceding stages of that task.

This should be distinguished from some similar concepts. First of all, it should be contrasted with the notion of *slowing the course of a stage.* This will be said to occur when there is an increase in the duration of the stage without any constraints being imposed upon its time of initiation. Second, the notion should be contrasted with delaying the completion of a set of stages by *insertion of a fixed delay between two stages.* The insertion of a delay between stages also affects the time at which a stage may begin, but not in a manner that is arbitrary with respect to progress in the preceding stages of the affected task. At the risk of belaboring the obvious, an analogy may make the difference between the three concepts clearer. Suppose someone is traveling from Point A to Point C in two separate legs by two different means of transit analogous to two stages of a single task. For instance, suppose a person is going from Point A to Point B by bicycle and from Point B to Point C by automobile. We may distinguish three different ways in which the total travel time might be increased. First, the bicycle might not be in good repair, slowing down that stage of the journey; this is analogous to slowing the course of the first stage. Second, the traveler might decide in advance to spend exactly 1 hr at Point B and then resume the journey; this inserts a fixed delay between stages. Third, the car to travel from B to C might not be available until some fixed point in time that happens to be after the traveler's arrival at Point B and that doesn't depend upon the time of arrival at B. This is analogous to postponement of the B-C stage.

Slowing and delay insertion, and their different effects in additive-factor type experiments, have been discussed in connection with the slowing produced by concurrent memory load (Egeth, Pomerantz, and Schwartz, 1977, November). It is probably obvious to the reader why one would wish to examine postponement in the context of overlapping stages: The bottleneck theories referred to above basically claim that the first task lengthens R2 by means of stage postponement, rather than by stage slowing or delay insertion. These models claim that a stage of the second task cannot begin until a central mechanism has switched from working on Task 1 to working on Task 2. Earlier stages of Task 2 are said to proceed automatically; they are *not* postponed. The present definition, then, fits the names applied to these models above.

We now consider how experimental manipulations could allow one to determine that an overlapping task situation was generating postponement, by selectively manipulating factors that slow particular stages. We will be asking what happens when the effects of a factor are compared in two situations: when the task is performed alone and when the task is the second of two overlapping tasks. Consider the simplest possibilities first. First, suppose that task overlap causes a postponement in the first stage of the second task. A clear prediction can be derived: The factor will slow R2 to the same extent as it slows the response to the same task performed alone.

Figure 1, Panel A illustrates this situation. Task 1 begins as soon as S1 is presented, but Stage 1 of Task 2 is postponed until time EP—the end of the postponement. The slowed Stage 1 (slowed by the factor) is represented as Stage 1'—the uppermost of the two boxes representing Task 2. The result is *additivity:* the slowing effects of the factor and the postponement sum to produce the final RT slowing. This is represented by the difference between R2 and R2' in the figure.

Bottleneck models that locate the postponement *later* in the second task make more surprising predictions. Suppose the task overlap condition means that some particular stage *after* the first stage cannot begin until a particular point in time: What happens when a stage in the task is slowed by a stimulus factor? If the factor slows down the *same* stage as that postponed by the initial task or a stage located *after* it in the S-R process, then the factor will add its own effects to the R2 slowing induced by the postponement. On the other hand, if the stage slowed by the factor is one that *precedes* the postponed stage in the sequence, then a distinctive result will emerge. When the

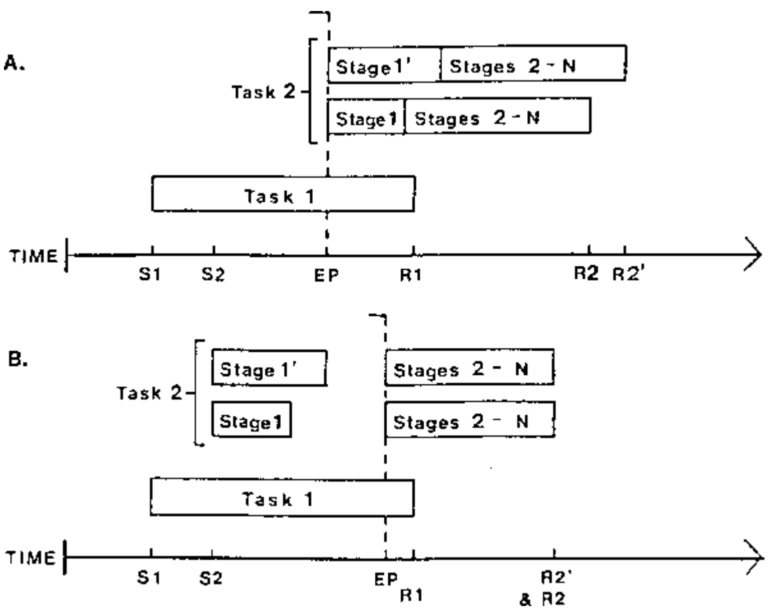

Figure 1, Panel A: Sequence of processing of Task 1 and Task 2 under a Stage 1 postponement model. (Task 2 is shown under two different levels of a factor that slows down the first stage. The slowed Stage 1 is represented as Stage 1' in the upper box of Task 2. The slowing results in a delay of R2 (to R2'). Panel B: Sequence of processing of the tasks under a Stage 2 postponement model. (Again, a factor is shown to slow down Stage 1, yielding Stage 1'. Now, however, the postponement washes out this difference and the final reaction times under both levels of the factor, R2 and R2', are identical.)

postponement caused by the overlapping task condition exceeds the slowing, no effects of the factor should be present in the overall R2 latencies. In short, it should be possible to reduce the effect of any factor that slows a stage earlier than a postponed stage. Of course, total elimination would depend upon the (unreasonable) assumption that the postponement and stage durations are fixed rather than distributed quantities. It is easy to see that as variance is added to the distribution of any of these parameters, complete elimination of factor effects will be replaced by a reduction. Thus, this type of model predicts *underadditive* interactions of task overlap and prepostponement factor effects.

This situation is represented in Figure 1, Panel B. In the figure, the *second* stage is postponed to point EP (end of postponement), and the factor manipulated slows down Stage 1 (yielding Stage 1'). Stage 1 or 1' proceeds during the time between presentation of S1 and the point in time at which postponement ends—EP. The R2 latences under both levels of the factor (R2 and R2') are now rendered equal by the postponement.

Specific Predictions

The perceptual postponement model is basically the Stage 1 postponement model of Figure 1, Panel A. It predicts that ail factors will have the same effects on RTs for the task performed alone and as the second of two tasks. According to the response-initiation postponement model (Keele & Neill, 1978), the cognitive work involved in both tasks proceeds without mutual interference. The initiation of the first response produces a postponement in the initiation of a second response. Therefore, this model predicts that stimulus factors delaying any stages in the second task prior to response initiation should have their effects reduced in the overlapping tasks condition. The decision-postponement model referred to earlier claims that the identification of stimuli proceeds in parallel with other mental operations, but that there is postponement of the decision and/or response selection processes. This makes the prediction that in the two-task condition the factors affecting encoding should have their effects on R2 reduced, whereas factors affecting later stages should have effects that are additive with the overall R2 slowing caused by the two-task condition. In summary, both decision postponement and response postponement predict some underadditivity of task overlap with stage-slowing factors but differ on how many factors should show this effect.

This kind of reasoning would remain applicable if stages continually feed one another in a cascading process (McClelland, 1979). If a late stage were postponed, then the previous stages could reach asymptote during the postponement period, reducing effects of factors slowing these earlier stages. Possibly, such results might also appear if the postponement itself were only "relative"—that is, the later stage might show a sluggishness of response that would gradually diminish with time. In general, it seems that the idea captured in the postponement notion (Figure 1) represents the discrete end of a continuum consisting of models with weaker or differing assumptions but sharing the notion that dual-task interference with central stages could cause early "automatic" stages to lose their status as rate-determining factors for the S-R process of which they are a part.[1]

Capacity Sharing and Factor Effects

The capacity-sharing approach to divided attention suggests a significantly wider range of ways in which these tasks can be combined. For instance, a particular task combination might be organized in the way described by one of the bottleneck models discussed, as a matter of strategy rather than necessity. However, the capacity view suggests another possibility, explored in detail in McLeod (1977b): that both tasks are slowed because both are performed simultaneously, reducing the resources available to each. Can the examination of factor effects reveal sharing in a particular task combination? I believe that it can, upon certain assumptions. Capacity sharing accounts for slowing most naturally if the speed with with each stage of a task is completed is held to be proportional to the amount of work involved in that stage divided by the available capacity. First, suppose that the amount of capacity available to each task is determined prior to each trial, this allocation remaining fixed for the trial's duration. This predicts that an increase in amount of work to be performed in a stage should have a *greater* effect in the two-task condition than it would in that task performed alone.[2] That is, work-increasing factors should interact *overadditively* with task overlap. Another possibility (proposed by McLeod) is that when R1 is completed, processing of S2 continues with full capacity. This should yield *additive* interactions between the second task factors and the task overlap variable.

A further possibility is that the allocation of capacity to the second task could vary with its difficulty: S2 might receive more capacity when it was more difficult. Compensating for S2 difficulty in this way could reduce the effect of the difficulty factor upon S2, simultaneously causing the S2 factor to show up in R1 slowing. In summary, then, capacity sharing models most straightforwardly predict overadditivity of factor effects and task overlap, but additivity might also be possible. More complex models might predict underadditivity if the stimulus factors altered the allocation policy, but then the factors should slow R1 as well.

It might be thought that these predictions could be assessed by examining data from the many published studies involving refractory effects. Unfortunately, these studies have generally manipulated factors that are likely to have, or have even been shown to have, widely dispersed effects. An example is the number of S-R alternatives, a factor explored in at least two studies of overlapping tasks (Karlin & Kestenbaum, 1968; Smith, 1969). Work in the additive factors tradition indicates that this factor has effects at both encoding and response selection (Sternberg, 1969a). In addition, it plainly affects the complexity of the task instructions the subject must hold in memory. If some of the slowing effects in this paradigm originate in lack of preparedness for

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[1] The author is indebted to Jeff Miller for emphasizing this broader class of models.

[2] A simple physical analogy may make this point clearer Suppose a 20-gallon bucket is to be filled with a hose producing 4 gallons/min; this will take 5 min. Reducing the flow (capacity depletion) to 2 gallons/min increases the time taken to 10 min, while increasing the size of the bucket to 28 gallons (amount of work) lengthens the time taken to 7 min. Decreasing capacity *and* increasing the work causes the task to take 14 min, an *overadditive* effect

the task (see Gottsdanker, 1980), then interactions would be expected however the two tasks are scheduled in time. In contrast, the experiments reported here employ only *stimulus factors* in mixed blocks. This at least gives one assurance that the factor cannot affect the state of preparedness that precedes the arrival of the stimulus. Logan's work on concurrent memory load effects (1978, 1979) provides a strong argument for the importance of this distinction among factors. All of the stimulus factors he investigated were found to have additive effects, with the slowing caused by the concurrent memory load (a result also obtained by Egeth, Pomerantz, & Schwartz, 1977, November). On the other hand, instructional factors like memory set size and number of S-R alternatives interacted overadditively with memory load (prior to extensive practice). As Logan suggests, this may indicate that the memory load affected preparation, rather than reducing the general capacity available to fuel the processing stages.

Related Work

This approach to the analysis of rapid successive tasks has some points of similarity to a number of previous studies. Keele (1973) argued for his response-initiation postponement model on the basis of Karlin and Kestenbaums (1968) finding that the difference between the R2 times for a choice and a simple detection task declined as the S1-S2 interval was decreased. Basically, he argued that the reduction in this difference indicates that the R2 slowing must result from a delay of stages beyond the particular stage where the choice/simple RT difference occurs. This conclusion requires accepting a basically subtractive analysis of the difference between choice and simple RT, that is, that the tasks are the same except for the extra stage. This does not seem especially plausible, in view of the many obvious differences between the two tasks (cf. E. Smith, 1968). Schweickert (1978) provided an analysis of an overlapping task situation that hinged on the same assumption. He applied his "generalized additive factors method" to some previously published data from a dual-task paradigm. His analysis depended upon the assumption that a task difference amounting to choice versus simple RT affected just the latency for the decision process; this is subject to the serious problem raised earlier.

Experiment 1

The first experiment employed a visual search task, which subjects performed either by itself (on half the blocks of trials) or as the second of two temporally overlapping tasks (on the other half of the blocks). The subject determined if a particular letter (the same throughout the experiment) was or was not present in an array of four letters; on half the trials it was present. In addition, the visual contrast of the entire array was varied between trials. The question of interest was how the effects of the experimental factors examined (contrast and target presence/absence) would be affected by placing the task as the second of two overlapping tasks.

Stimulus contrast has been extensively used as a manipulation of the duration of the encoding stage of information processing (e.g., Hardzinski & Pachella, 1980). There is substantial evidence that stimulus quality factors are additive with factors supposed to affect later, more central stages, for example, memory set size in a memory search task (Sternberg, 1969b; Hardzinski & Pachella, 1980), decision difficulty in a task involving arrow stimuli (Schwartz, Pomerantz, & Egeth, 1977), or display size in a visual search task (Johnsen & Briggs, 1973; Logan, 1978).

The presence or absence of the target presumably must affect a stage involving the decision or response selection. The precise locus of this effect is not known, and it may depend upon the exact strategy employed in the search task, which in turn may vary substantially from experiment to experiment. For instance, target presence/absence is sometimes additive with display size (e.g., Atkinson, Holmgren, & Juola, 1969)—suggesting that these factors affect different stages—but the two factors also sometimes interact (e.g., Logan, 1978). In some cases, the slope of the display size RT function is about twice as steep for the target-absent trials than for the target-present trials, suggesting that the display might be searched in a serial self-terminating fashion (Schneider & Shiffrin, 1977). Logan (1978) has suggested that smaller arrays (perhaps one to rive; the present experiment uses four) are searched exhaustively, whereas larger ones may be searched in a self-terminating mode. Of course, parallel search is also very much a possibility. What is crucial for the present work is just that the presence/absence factor presumably affects postencoding processes involved in decision and/or response selection.

Method

Subjects. Eight University of Pennsylvania students were paid for their participation in two 1-hr sessions.

Apparatus and stimuli. The stimulus presentation and response collection were controlled by microcomputer. The sequence of stimuli was the same whether the subject was performing two tasks or only one. The stimulus for the first task consisted of a bright bar composed of four connected white spaces one character in size, presented three text lines (approximately 3.8° visual angle) above or below the fixation point. The stimulus for the second task consisted of a centrally presented array of four letters, separated by one space horizontally and one text line vertically (1.7° X 1.9° visual angle). The first 20 uppercase letters were used as distractors, whereas the uppercase letter *F* served as a target for all subjects. Contrast reduction was accomplished by presenting the letters in a dark grey color from the microcomputer's standard color array (about 0.9 footlamberts or 3.09 cd/m^2). The background was black throughout (about 0.4 footlamberts or 1.37 cd/m^2), and the high-contrast letters were presented in white (about 45.0 footlamberts or 154.35 cd/m^2). This produced a modest but consistent contrast effect, without excessive elevation in error rates. The index and middle fingers of the left hand were used for the first response, whereas the index and middle fingers of the right hand were used for the second response. The subject pressed the *X* key if the bar of light was above the center of the screen, and the *Z* key if it was below. The (.) and (/) keys corresponded to no and yes, respectively, for the second task.

Design. The experiment was divided into one practice block (not analyzed), followed by 10 experimental blocks, alternating between two-task and one-task blocks. Each block consisted of 80 trials, 20 in each combination of target presence/absence and contrast. The order of trials was randomized individually for each subject.

Procedure. The general instruction was to respond as quickly as possible while remaining as accurate as possible. The subject was instructed to respond as quickly as possible to both tasks in the two-task blocks, with the restriction that the first stimulus must be responded to before the second. Feedback was presented for the second response times and total errors, in the two-task condition. The subjects were advised that the computer did not proceed until two responses in that order were obtained: they did not appear to have trouble complying. Each trial began with the presentation of a fixation dot in the middle of the screen, lasting 400 ms. One hundred ms after its offset, the first stimulus appeared above or below the center of the screen, remaining present for 67 ms. The letter array appeared in the center of the screen 100 ms after the onset of the first stimulus and remained on the screen until the subject made both responses. The intertrial interval was approximately 2 s. Response times longer than 1.5 s were discarded.

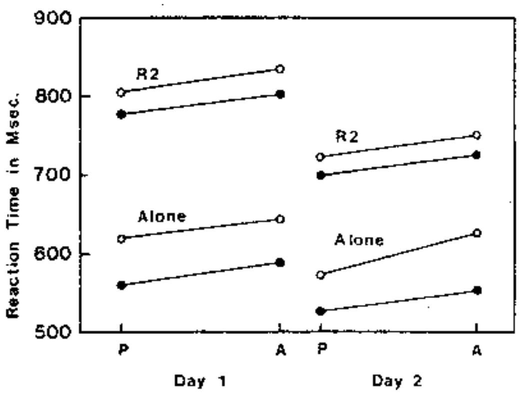

Figure 2. Reaction times for visual search task when performed *alone* or as the second of two tasks (R2) in Experiment 1. (Filled circles = high contrast; unfilled circles = low contrast; P = target present; A = target absent.)

Results

The results averaged over subjects and sessions are presented in Figure 2. The response to the letter array took an average of 179 ms longer when it was made as the second of two responses. This was a highly significant difference, *F*(1, 7) = 62.0, $p < .0001$. Contrast reduction produced a slowing of 58 ms when the search task was performed alone, but only 28 ms when the search task was the second of two tasks. The overall contrast effect was significant, *F*(1, 7) = 42.6, $p < .001$. The interaction of task overlap with contrast was also significant, *F*(1, 7) = 12.1, $p < .01$. Subjects were 31 ms slower to respond no than yes in the one-task condition, compared to 27 ms in the two-task condition. This presence/absence effect overall was significant, *F*(1, 7) = 10.8. $p < .02$. The interaction of presence/absence with task condition was not significant. *F*(1, 7) = .38, $p > .50$. There was a significant interaction of Day X Contrast X Target Presence/Absence, *F*(1, 7) = 6.4, $p < .05$, but no other interactions were significant.

The R1 latencies and the error rates are shown in Table 1. The effects of the task factors were mirrored more weakly in the R1 latencies, but only the effects of sessions were significant, *F*(1, 7) = 9.8, $p < .02$. S2 contrast was not significant. *F*(1, 7) = 2.0, $p > .15$. nor was S2 target presence, *F*(1, 7) = 2.6, $p >$

Table 1
Error Rates and R1 Latencies—Experiment 1

	Session 1			Session 2		
Target	R1 time (ms)	Error % Task 2 alone	Error % R1 or R2[a]	R1 time (ms)	Error % Task 2 alone	Error % R1 or R2[a]
Present						
Low contrast	710	4.2	9.9	653	4.1	8.2
High contrast	698	4.2	6.4	641	3.1	8.6
Absent						
Low contrast	721	1.4	6.7	678	1.9	6.7
High contrast	703	1.4	5.1	653	1.5	6.0

[a] Proportion of dual-task trials on which one or both responses was an error.

.15. There was also a significant tendency for more errors in the two-task block. Otherwise, differences among error rates were not significant. The average correlations between the R1 and R2 times were .71 and .81 for the first and second sessions, respectively. This data will be discussed later in the Discussion of Experiments 1-4.

Discussion

The requirement to perform a first task produced a highly significant R2 slowing effect in the visual search task. What is crucial to the present analysis, however, is the fact that this slowing was strongly underadditive with the slowing due to contrast reduction, but additive with the effects of target presence/absence. In the introduction, a class of models was described that would predict such underadditivity: the decision postponement model. If one source of the R2 slowing with this task combination is a *postponement* of a stage beyond the locus of at least some of the contrast effect, then a reduction in the contrast effect in the two-task condition is to be expected. To put it differently, a natural account of the underadditivity is that the processing stage(s) affected by contrast proceeded in parallel with performance of the first task, whereas some later stage did not begin until the completion of the first task. The data places a further constraint on this natural type of model: There cannot be significant postponement of any stage *beyond* the stage affected by target presence/absence. It seems reasonable to speculate that this factor affects a stage involved in memory comparison and/or response selection. This issue is explored more in the Discussion of Experiments 1-4 later.

Thus, the results fit nicely with the predictions of one of the three bottleneck models sketched above: the decision postponement model. The perceptual postponement model, which claims postponement of all perceptual processing, cannot account for the reduction in contrast. On the other hand, the response-initiation postponement model cannot account for the persistence of the target presence/absence difference in the overlapping task condition.

The R1 latencies show a nonsignificant trend toward slowing on account of S2 difficulty factors. This might be accounted for in terms of capacity sharing or, alternatively, a strategy of response grouping. This issue will be discussed after the presentation of Experiment 4.

Experiment 2

The next experiment was performed for two purposes. The first was to extend the investigation of Experiment 1 and determine whether the effects of another factor—display size—are affected by the placement of the search task as the second of two speeded overlapping tasks. The second purpose was to replicate the finding of the first experiment that the magnitude of the target presence-absence effect is not changed by the task condition. This is important because the finding indicates that the response selection processing on these tasks is *not* completed without interference, as some (e.g., Keele, 1973) have suggested it is.

Johnsen and Briggs (1973) and Logan (1978) found that display size in a search task was additive with visual noise degradation, which would seem to argue that the display size variable employed here affects the duration of a process that is functionally separate from that affected by stimulus quality. It is therefore of interest to determine whether some of the work of this stage of processing can go on simultaneously with the subject's involvement in another task, or alternatively, whether it must be postponed.

Method

Subjects. Eight undergraduates from the University of Pennsylvania served as subjects in two 1-hr sessions in return for payment.

Apparatus and stimuli. Collection of data was controlled by a microcomputer, and the stimuli were presented on a cathode-ray tube (CRT) screen. The stimuli were nearly identical to those of Experiment 1, although the experiment was run on a different microcomputer. In the two-task condition, the stimulus for the initial task consisted of a white patch (three mottled white square characters in a row) presented two text lines (approximately 1.8° visual angle) above or below the fixation point. S2 consisted of an array of letters, containing two, four, or six items. The display consisted of one, two, or three vertical pairs of letters, separated horizontally by a single character space. Thus the display measured two vertical text lines (1.1°) high by one. three, or five horizontal text spaces wide (.6, 1.3 or 2.1°). On half of the trials, the array contained a target *Y;* on half, it did not. The distractors were drawn at random from the set of letters from *A* to *X*.

Design. Each session was divided into 10 blocks of 72 trials per block. One- and two-task blocks alternated. Within each block, there were 12 trials for each combination of set size (two, four, or six letters) and presence/absence of a target.

Procedure. The subjects performed 792 trials per session; the first 72 were practice only. The two-task trials consisted of the following sequence of stimuli. First, a fixation point appeared on the screen for 500 ms. Five hundred ms after its onset, the white patch stimulus for the first task appeared either above or below the fixation point, and the subject responded by pressing one of two left-hand response keys (the *Z* and *X* keys on the keyboard). The display lasted 67 ms. and 100 ms after its onset, the array of letters was presented. It remained on the screen until the subject had responded with one of two right-hand keys: the (/) key for yes and the (.) key for no.

Results

The mean R2 latencies are presented in Figure 3. The effect of task overlap (R2 slowing) averaged 254 ms and was significant. *F*(1, 7) = 60.6. $p < .001$. Other significant main effects were those of sessions, *F*(1, 7) = 25.8, $p < .002$, display size, *F*(2, 14) = 49.6, $p < .0001$, and target presence/absence, *F*(1, 7) = 9.9. $p < .02$. Underadditivity of task condition and display size is evident in Figure 3: For both present and absent trials, the upper two lines have a smaller increase (51 ms and 57 ms, respectively) than the lower two lines (84 and 109 ms, respectively). This interaction of display size and task condition was significant, *F*(2, 14) = 6.9, $p < .01$. There was no interaction of R2 slowing due to task overlap and target presence/absence, *F*(1, 7) = 0.26, $p > .60$. Other interactions were not significant.

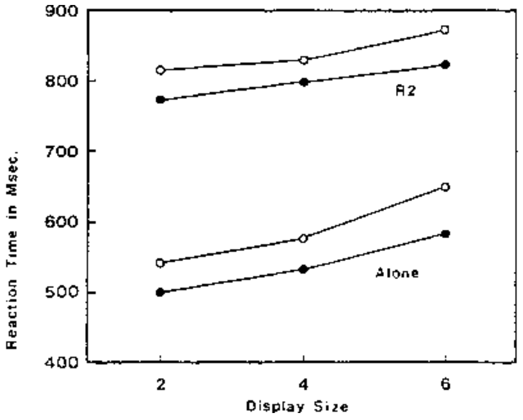

Figure 3. Reaction times for visual search task when performed *alone* or as the second of two tasks (R2) in Experiment 2. (Filled circles = target-present trials; unfilled circles = target-absent trials.)

Table 2 presents the error rates and R1 latencies for the different task 2 conditions. The R1 latencies exhibit a consistent trend toward mirroring the pattern of the R2 latencies in their dependency upon each of the S2 factors; however, these effects are not significant. The stimulus factors did not significantly affect error rates. The correlation of R1 and R2 response times averaged .68 and .79 for the first and second sessions, respectively.

Discussion

These findings have a number of strong implications for the various theories of the refractory period, converging with the observations of the first experiment. The result of Experiment 1, that the target presence/absence effect is unchanged when the task is performed as a second task, is replicated in this experi-

Table 2

Error Rates and R1 Latencies—Experiment 2

	Two- task condition		One-task condition
Target	R1 time (ms)	Error % R1 or R2[a]	Error %
Present			
Display size = 2	678	9.2	1.9
Display size = 4	694	9.5	3.3
Display size = 6	721	12.6	5.4
Absent			
Display size = 0	703	9.3	2.3
Display size = 4	709	7.6	1.9
Display size = 6	718	8.6	2.2

[a] Proportion of dual-task trials on which one or both responses was an error.

ment. Therefore, the R2 slowing is not a case of response postponement. If response initiation were the only bottleneck responsible for R2 slowing, then factor slowing all stages prior to response initiation should have their effects reduced or eliminated. Second, there is evidence supporting postponement of a stage beyond that affected by display size. The results of this experiment indicate that the display size effect is significantly reduced in the two-task condition, just as the previous experiment showed underadditivity of stimulus contrast with the task condition.

The decision postponement model, described in the introduction, provides one quite natural account of the data. The early stages of the task—those involving encoding and memory comparison—can proceed, at least to some degree. Clearly, this parallel processing is not completed on every trial, like that illustrated in Figure 1, Panel B, or else the factor would have zero effect in the two-task condition. Thus, when the subject is done with the first task, the amount of work remaining to do on the earlier aspects of the task is (on many trials) reduced, and the factors slowing them down do not produce their full effects in R2 latencies. But, on this account, after switching from first to second task, the subject still must complete the decision-making and response-selection stages, and therefore the target presence/absence effect is intact in this condition.

Experiment 3

The previous experiment indicated that with the short stimulus onset asynchrony (SOA) (100 ms), the effect of the size of the display in a visual search task is reduced when the search is performed as the second of two overlapping tasks. We conclude, therefore, that there is some postponement going on. However, it seems worthwhile to try to determine if the pattern of data changes when S1 and S2 are separated by a longer SOA. For instance, it is possible that the postponement is only one component of the R2 slowing. At longer S1-S2 intervals, this component might not contribute to the effect, whereas other components might remain. Therefore, the third experiment was conducted with a longer SOA between S1 and S2 (300 ms).

Method

Subjects. Seven University of Pennsylvania students served as subjects in two 1-hr sessions.

Stimuli and design. The stimuli and design were like those of Experiment 2, with the following exceptions. The target in all cases was the digit 9, instead of a letter. The distractors were the nine other digits, instead of other letters. Within-category search for letters and for digits has not been reported to differ qualitatively. As in Experiment 2, each subject performed 792 trials per session.

Procedure. The procedure followed that of Experiment 2, the only difference being the longer stimulus onset asynchrony between the two displays (300 ms).

Results

Figure 4 presents the mean R2 latencies as a function of task overlap, display size, and target presence/absence. The overall effect of sessions was significant, $F(1, 6) = 11.93$, $p < .05$, as were the effects of task condition. $F(1, 6) = 26.9$, $p < .005$, display size, $F(2, 12) = 25.6$, $p < .001$, and presence/absence. $F(1, 6) = 18.4$, $p < .01$. There were no significant interactions of display size and task condition. $F(2, 12) = 1.92$, $p > .10$, nor of target presence/absence and task condition, $F(1, 6) = .49$, $p > .50$. There were indications of a reduction in display size with practice (Sessions x Display Size, $F(2, 12) = 11.6$, $p < .005$. The display size slopes were steeper for the *no* trials than for the *yes:* The interaction of display size with presence/absence was significant, $F(2, 12) = 23.2$, $p < .001$. Other interactions were not significant. Table 3 presents R1 latencies and

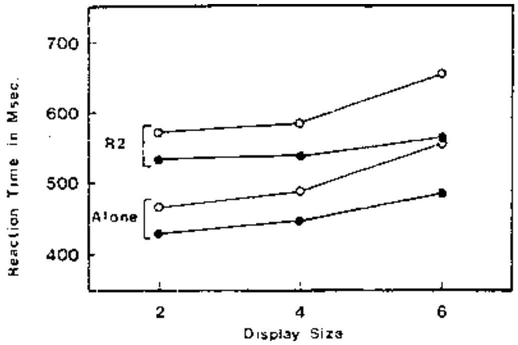

Figure 4. Mean reaction times for visual search task performed *alone* or as the second of two tasks (R2) in Experiment 3. (Filled circles = target-present trials; unfilled circles = target-absent trials.)

the error rates. R1 latencies show only the most minimal trend toward dependence upon S2 factors, unlike in the earlier (shorter SOA) experiments. The implications of this will be discussed later. The average correlation of R1 and R2 was .22 and .28 for the first and second session, respectively.

Discussion

The results indicate that the pattern of underadditivity observed between display size and task condition in Experiment 2 does not appear to a significant degree when the stimuli for the initial and primary tasks are presented further apart in time. There is no indication of underadditivity in either session. We can infer from the pattern of data in this and the previous experiment that the postponement that Experiments 1 and 2 argue for is not the only kind of task interference contributing to the R2 slowing caused by task overlap. Experiment 2 indicates that some of the processes affected by display size can proceed to some degree during a period in which a later stage is postponed. Experiment 3, with a longer interval between stimuli shows no such evidence. However, a substantial R2 slowing (95 ms) remains. Therefore, R2 slowing in general can result from some form of task delay *in addition to* the postponement noted above. The nature of this remaining R2 slowing is not determinable from the present data. Using the terms defined above, it most likely involves either a *slowing* of some stage, such as decision or response selection, or the insertion of delay(s) between stages.

Table 3
Error Rates and R1 Latencies—Experiment 3

	Two-task condition		One-task condition
Target	R1 time (ms)	Error % R1 or R2[a]	Error %
Present			
Display size = 2	538	4.4	4.2
Display size = 4	534	6.1	7.3
Display size = 6	543	8.0	6.5
Absent			
Display size = 2	542	5.2	1.7
Display size = 4	541	3.6	2.2
Display size = 6	574	6.7	2.1

[a] Proportion of dual-task trials on which one or both responses was an error.

It seems plausible to speculate that this additional delay in R2 inferred from the results of Experiment 3 may be the result of poor preparation for the second task, rather than any need to postpone part of the second task because of continuing involvement in the first task. With this 300 ms SOA, it seems possible that the subject has already issued motor commands for R1 by the time S2 has been encoded, because the average R1 latency is just 545 ms. There is plenty of circumstantial evidence that some R2 slowing results from preparation failure. For instance, R2 slowing can occur even when S2 follows R1 in time (e.g., Davis, 1957), and Gottsdanker (1979) has shown an R2 slowing on trials when Rl is expected but omitted.

Experiment 4

The finding of Experiment 2 (underadditivity of the effects of display size and task condition with the 100-ms SOA) seems to be worth exploring in more detail. By the reasoning developed in the introduction, the results suggest that at least much of the encoding and comparison process can be carried out during a period of postponement—presumably while a central mechanism is engaged in work on the first tasks. It is possible that this parallel processing depends upon the increasing automaticity of the comparison or search stages. In that case, parallel processing might not occur if the procedure was changed to prevent the subject from gaining consistent practice searching for particular stimuli.

Schneider and Shiffrin (1977) have shown that such practice is necessary for the development of automatized visual search (as indexed by an eventual flattening of the memory set and display size functions). Similarly, Logan (1979) has found that the interaction of the slowing effects of an external memory load with number of S-R alternatives disappears only if consistent practice is provided. Logan's results may be the more relevant if, as he argues, the disappearance of interactions with concurrent memory load indexes automaticity of the task, whereas disappearance of the display and memory set size effects in Shiffrin and Schneiders paradigm indexes perceptual learning of the stimulus set. Logan reports that about 840 trials in either single- or dual-task conditions are sufficient to produce the disappearance of the interactions of memory load with memory set size (1978) or number of S-R alternatives (1979). Experiment 2 reported here involved 1260 trials per subject, so it is reasonable to think that automaticity would be developing, as measured by his criteria.

In order to see if consistent target assignment plays a role, the present experiment therefore adopted the varied-mapping condition, whereas the previous experiments employed a consistent assignment of targets. On each trial of this experiment, the subjects were presented with a different single target to search for in the array that followed. Both the targets and the distractors were drawn from the alphabet with no particular restrictions: Thus, a target on one trial might be a distractor on another.

Method

Subjects. Eleven University of Pennsylvania students were paid to participate in two sessions each lasting approximately 1 1/2 hr.

Stimuli. The stimuli were presented exactly as in Experiment 2, except for the following. Prior to the onset of each trial, the computer presented the word *target* followed by the single letter designated as the target. The target was selected at random from the entire alphabet; the distractors were chosen at random from the remaining letters.

Design. The experiment was divided into 20 blocks of 30 trials, alternating by task overlap. All six combinations of display size and target presence/absence were equally represented within each block.

Procedure. The target for the current trial was presented for 1 s, followed by 1-s blank screen; then the sequence followed Experiment 2.

Results

The R2 latencies, R1 latencies and error rates are presented in Table 4. The effect of display size was significant, $F(2, 20) = 48.0$, $p < .0001$, as were the effects of sessions, $F(1, 10) = 103.4$, $p < .0001$, task overlap F(1, 10) - 87.0, $p < .0001$ and target presence/absence, $F(1, 10) = 24.1$, $p < .001$. There was no significant interaction of display size and task condition, $F(2, 20) = 2.5$, $p > .10$, nor of target presence/absence and task condition, $F(1, 10) = 1.9$, $p > .15$. There was a nonsignificant trend for the R1 latencies to lengthen with the S2 factors, as in both of the earlier experiments using the 100-ms SOA.

Discussion

In this experiment, subjects searched for a different target on each trial, and a previous target could occur as a distractor. There was no significant reduction of the display-size slope for the R2s performed in the two-task condition. On the other hand, there *is* still some trend in that direction. Thus, the significant reduction observed in Experiment 2 *may* be due to the development of stimulus-specific practice. It appears that a more definitive analysis of the role of stimulus-specific practice in these results would be worthwhile. It should probably explore the effects of larger amounts of practice, using a within-subject comparison. This would make it possible to determine whether a systematic practice-dependent change is taking place. In any case, the results provide a suggestion that inconsistency of target assignment results in a smaller amount of automatic processing of S2 being completed during the postponement period.

Equally important, the results also replicate the finding of the previous three experiments that the target presence/absence effect is not reduced when a search task is performed as the second of two tasks in rapid succession. This argues against the view (Keele, 1973) that all of the preresponse processing of S2 occurs in parallel with the first task.

Table 4
Reaction Times and Error Rates—Experiment 4

Target	Two-task condition			One-task condition	
	R2 time (ms)	R1 time (ms)	Error % R1 or R2[a]	Time (ms)	Error %
Present					
Display size = 2	713	646	18.6	505	4.9
Display size = 4	724	650	19.6	516	7.8
Display size = 6	758	682	18.4	553	8.8
Absent					
Display size = 2	751	658	13.4	525	5.6
Display size = 4	785	680	15.6	547	3.9
Display size = 6	813	695	16.6	611	5.7

[a] Proportion of dual-task trials on which one or both responses was an error.

Discussion of Experiments 1-4

Experiments 1-4 provide evidence against a number of previously proposed accounts of R2 slowing, in the case of the task combination used here.

1. The R2 slowing is not the result of postponement of response initiation, because the yes/no effect is not reduced in any experiment.

2. The R2 slowing does not result solely from postponement of encoding of the second task, without other changes, because this would not account for the reduction in contrast and display size effects.

3. The R2 slowing does not result solely from sharing of a capacity involved in ail of the stages, *if* one assumes that the amount of capacity allocated to each task does not change with the S2 factor level.

On the more affirmative side, it has been suggested that postponement of the decision and/or response selection stages provides a very natural account of the results obtained thus far. Such a postponement should yield underadditivity with factors affecting earlier stages; a plausible pattern of underadditivities was in fact observed. However, more complex capacity-sharing schemes cannot entirely be ruled out. One such possibility is that the underadditivity is produced by the subjects' adopting a policy of allocating more capacity to the second task when the factor level makes the task more difficult. This could, on certain assumptions, result in those factors having smaller effects in the two-task condition than the one-task condition.

It would also predict that the first task should suffer more under these circumstances. In fact, such a trend is evident in the data. In Experiments 1, 2, and 4, there was a consistent trend for R1 latencies to be longer when the S2 factor was more difficult. However, this trend appears for factors that were underadditive in R2 latencies *and* the factor that was not (target presence/absence). Of course, these trends might be spurious, but they do suggest that the dependence of R1 upon S2 factors has some origin other than rapid reallocation of capacity.

An alternative account of R1 slowing would be response grouping: a strategy of emitting R1 only after both R1 and R2 have been selected.[3] If subjects group on a certain proportion of trials, then R1 should be delayed by all S2 difficulty factors at some fixed proportion of the factors' effects upon R2. This strategy would be entirely consistent with various bottleneck accounts. Various aspects of the data suggest this may be going on. and previous research has suggested that this may be a common strategy (e.g., Gottsdanker & Way, 1966). The pattern of correlations of R1 and R2 latencies provides one piece of evidence. In Experiments 1 and 2 (shorter SOA), the averaged R1-R2 correlations for a session

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[3] This term has occasionally been used to refer to something different, namely, treating S1 and S2 as a unit and *selecting* R1 and R2 as a corresponding unit. Here the term refers to the pattern of response initiation, not 10 response selection.

were very high (ranging from .68 to .81). This indicates a low variability of the interresponse intervals (IRIs) relative to the variances of either response time, which is exactly the pattern one would expect if the responses were emitted with very little intervening cognitive work. In Experiment 3 (longer SOA), on the other hand, the correlations were substantially moderated (averaging .25), indicating greater independence of the two response times. This difference between the experiments suggests that the short SOA induces subjects to group responses. Gottsdanker and Way (1966) have reported observations quite consonant with this: For their short SOAs (50 & 100 ms), the R1-R2 correlations were distinctly elevated, but only when SOA itself was blocked (hence predictable). These data make sense if subjects can adopt in advance a strategy of grouping responses but choose to do this only when it does not excessively delay R1. Of course, other factors could produce a higher R1-R2 correlation with shorter SOAs, but the dependence upon predictability in Gottsdaker and Way's data, and the extremely high correlations observed here, are suggestive of grouping.

The absolute R1 times also suggest a grouping strategy at the shorter SOA: The R1 was approximately 150 ms longer in Experiments 1 and 2 than in Experiment 3 for the same R1 task. In those experiments, the average IRI was about 200 ms, whereas it was over 300 ms at the longer SOA. Elevation of R1 times with short blocked SOAs, was also found by Gottsdanker and Way. Thus, three aspects of the data—S2 effects on R1, response and IRI variability, and absolute response times—converge to suggest that the shorter SOAs may be encouraging a grouping strategy, a possibility that has been widely suggested by earlier workers.

Experiment 5

It has been argued that postponement of decision and/or response selection provides a very economical way to account for the pattern of additivities and underadditivities reported earlier. However, it was conceded that the possibility that the stages of both tasks are being performed simultaneously, but with depleted capacity, cannot be completely rejected, if one allows the possibility that capacity allocation is being strategically altered in a complex fashion. One very strong reason for considering the possibility of general capacity sharing in speeded overlapping tasks is the typical occurrence of R1 slowing in these paradigms. In the earlier experiments, subjects did not perform R1 alone, so this slowing was not measured. However, the first task was very easy, and informal observations suggest an R1 slowing on the order of several hundred milliseconds with the 100 ms SOA. The present experiment uses factorial manipulations like those in the previous experiments to examine R1 slowing in detail.

There are at least two natural accounts of R1 slowing. One is response grouping: a strategy of withholding R1 until R2 has been selected. Grouping is compatible with any of the bottleneck models, and various aspects of the data consistent with it (S2 effects on R1 latencies, R1-R2 correlations) have been discussed earlier. But sharing of capacity between both tasks (McLeod, 1977b) also provides an undeniably natural an account of how R1 might come to be slowed.

Fortunately, the two accounts make different predictions when stimulus factors are manipulated in a task performed either as the *first* of two tasks or alone. It can be seen that response grouping makes a very simple prediction: *Any* S1 factor lengthening R1 performed alone will have the same effect on R1 in the overlapping task condition, and also the same effect on the R2 in the overlap condition, as it has on the first task performed in isolation. This holds regardless of what proportion of the time grouping occurs so long as the factor does not change the probability of grouping on particular trials.

Capacity sharing makes very different predictions. If the allocation of capacity does not vary with the factor level, then increasing the amount of work to be performed in a stage (the factor), and depleting the capacity (task overlap) should yield an *overadditive interaction.* Suppose, on the other hand, that the capacity allocation policy *does* vary with the level of the factor. It was suggested previously that the results of Experiments 1-4 could conceivably be accounted for on such a scheme. The present consequence of this possibility is clear: In the overlapping task situation, the factor effects would be free to vary. Overcompensation in allocation would yield underadditivity, undercompensation would yield overadditivity, and additivity would be coincidental. Furthermore, if rapid reallocation were occurring in the earlier experiments (a possibility that could not be entirely discarded), it would be natural to expect it here as well. More specifically, if subjects generally overcompensate for these stimulus factors (producing the underadditivity of Experiments 1 and 2), the same should probably be expected here.

In summary, response grouping predicts additivity, whereas capacity sharing predicts either overadditivity or any pattern whatever, the latter if the allocation policy is determined by the level of the stimulus factor.

Method

Subjects. Seven University of Pennsylvania students participated in two 1-hr sessions in return for payment.

Apparatus and stimuli. The apparatus used was identical to that of the previous three experiments. The two tasks combined were also identical. One was a visual search task for a specified letter target that remained constant throughout the experiment. The arrays again consisted of two, four, or six letters. The second task consisted of locating the briefly flashed bar of light above or below the center of the screen. There were two differences between this experiment and Experiment 2. First of all, the visual search task occurred either alone of as the first of two tasks in the two-task blocks. The responses to it were always made first and always with the left hand. The assignment of response keys was the same except for the hand reversal. The other difference was in the SOA between the stimuli for the search task and the stimuli for the up-down task. The stimuli were presented *simultaneously* in this experiment in order to maximize the opportunity and incentive for parallel performance with capacity sharing, if such a strategy is available.

Design. The design was identical to that of Experiment 2.

Results

The average RTs for the search alone, the search as the first of two tasks (R1), and times for the R2s following these R1s on the two-task trials, are all graphed in Figure 5, as a function of the display size and target presence/absence in the search task (S1). The additivity apparent in the figure was confirmed statistically. There is a highly significant slowing of the first reaction time (the search task) when it is placed as the first of two tasks, $F(1,\ 6) = 51.8$, $p < .001$. Similarly, there are significant effects of display size, $F(2,\ 12) = 50.2$, $p < .0001$, and target presence/absence, $F(1,\ 6) = 14.5$, $p < .01$. Though there would seem to be a hint of overadditivity of presence-absence with task condition on inspection of Figure 5, it does not approach significance, $F(1,\ 6) = 1.7$, $p > .2$, despite the highly significant main effects. Nor is there an interaction between condition and display size, $F(2,\ 12) = .47$, $p > .5$.

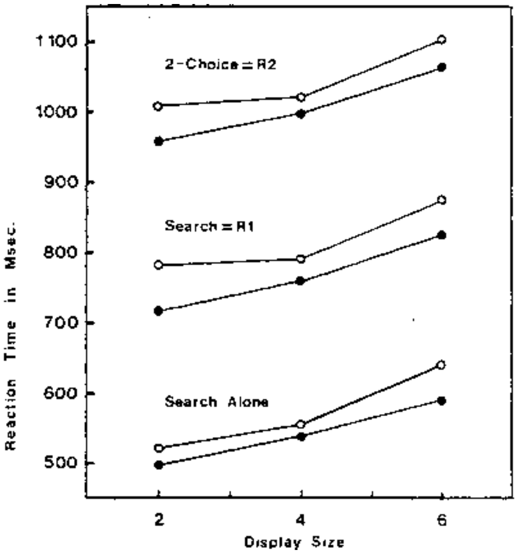

Figure 5. Mean reaction times for visual search task when performed *alone* or as the first of two tasks (R1) in Experiment 5. R2 represents RT for second task in the same two task trials as R1. (Filled circles = target present; unfilled circles = target absent.)

The error rates are presented in Table 5. There were no significant differences as a

Table 5
Error Rates — Experiment 5

Target	Two-task condition[a]	One-task condition
Present		
Display size = 2	6.3	4.6
Display size = 4	9.2	6.8
Display size = 6	10.7	9.4
Absent		
Display size = 2	8.3	3.8
Display size = 4	7.5	4 4
Display size = 6	7.5	5.5

[a] Proportion of two-task condition trials on which one or both responses was an error.

function of the experimental factors. The average correlations of R1 and R2 times were .72 and .78 for Sessions 1 and 2, respectively.

Discussion

The simultaneous presentation of the stimuli in this experiment produced a highly significant increase in R1 latency. The increase might be due to response grouping, or it might be due to capacity sharing (McLeod, 1977b). The data reported here follow the predictions of the grouping account, but they are not especially congenial to the suggestion that the stages of the first task are slowed because they are performed at depleted capacity, simultaneously with the second task. On that account, increases in the work load (display size, target presence/absence) should have a greater effect upon R1 when the capacity is only partially available (task overlap condition) than when it is fully available (R1 alone condition). Instead, it is observed that the effects of both factors do not differ significantly in any of the three categories (R1 alone, R1 together, and R2). If the general sharing model were accounting for the slowing, but the capacity allocated to Task 2 depended upon the Task 1 factors, then the additivity reported here would be coincidental. This study, therefore, provides further reason to believe that the overall delay in R1 is not the result of simultaneous work on both tasks with capacity sharing. Following the reasoning described earlier, the very high R1-R2 correlations also suggest a response-grouping strategy.

It should be emphasized that the data do not rule out the possibility that *both* capacity sharing and response grouping are occurring in this experiment. This is certainly possible, but once grouping is postulated, the existence of the R1 slowing no longer provides any particular support for capacity-sharing model. And it is the R1 slowing that has provided the strongest support for the capacity-sharing approach to overlapping tasks (e.g., McLeod, 1977b; Kahneman, 1973).

General Discussion

Five experiments have been reported comparing the effect of experimental factors affecting stages of processing in a search task, when that task was performed by itself and as one of two tasks performed in temporal overlap. In the first experiment, the effect of display contrast upon RTs was substantially decreased when the subject was required to perform a choice task immediately prior to the search task. In the second experiment using very similar tasks, the effect of display size was reduced in the two-task condition, but again the target presence/absence effect was not changed. No reduction in the display size effect was observed with the search task when the S1-S2 interval was increased from 100 to 300 ms, although a substantial R2 slowing remained (Experiment 3). Display size was also not significantly underadditive when a varied-mapping search condition was employed at the 100 ms S1-S2 interval (Experiment 4).

This pattern of results follows naturally from the idea that early processing in a visual search task occurs in parallel with the work on the first task (and possibly automatically, in the sense of Posner, 1978), while some later decision-making processes (speaking very broadly) must be postponed. Equally important, the data differ fairly strikingly from the predictions of several alternate approaches to overlapping tasks sketched at the beginning of the paper: perceptual postponement, response-initiation postponement, and parallel capacity-depleted processing.

First of all, the data provide no support for theories claiming a bottleneck in the initial analysis of perceptual information. Some of the encoding and comparison process may be presumed to proceed in parallel with the work of the second task, based upon the substantial reduction observed in the contrast effect (Experiment 1) and the display size effect (Experiment 2). Another alternative model has suggested a bottleneck late in processing, at the point of response initiation (Keele & Neill, 1978). This model seems to have overestimated the extent of the overlapping processing in overlapping task situations, at least for cases involving limited practice and similar input and output modalities for both tasks. If response selection were fully automatic, with postponement located beyond, we should find a reduction in the effects of *all* factors in the two task condition. Experiment 1-4 showed no tendency for the target presence/absence effect to be reduced in the two task condition, despite the sometimes very large overall R2 slowing.

The situation with regard to capacity sharing is somewhat more complex, which is to be expected given the flexibility of this notion. The question at issue here is not whether capacity sharing is possible at all, but whether it can explain the slowing observed with this particular task combination (McLeod, 1977b). The simplest way in which it might is if the subject decides in advance how much capacity to allocate to each task; the stages of both tasks then proceed in parallel, but more slowly because of the reduced available capacity. This kind of model can be simply rejected by Experiments 1-5, because no hint of overadditivity appeared. Another possibility is that the subject might allocate capacity differently depending upon task factors. This might possibly explain the selective underadditivities in R2 effects observed in Experiments 1-4, if some factors were compensated for, while others were not. However, the data exhibit a trend for R1 to be slowed whenever any factor slowed R2, including target presence/absence, which was itself additive in R2; naturally, these trends may not be reliable.

A major reason for suspecting that general capacity sharing occurs in overlapping tasks has been the occurrence of R1 slowing. In Experiment 5 I examined R1 slowing while manipulating stimulus factors in S1. If R1 slowing is attributable to performance of the first task with reduced capacity, then these work-increasing factors should have greater effects on R1 in this condition than they have in the same task alone, assuming that capacity allocation is fixed with respect to variation of the factor. If capacity allocation changes, then any pattern of factor effects is possible, from over- to underadditivity. If subjects characteristically overcompensate for display size (which could possibly account for the data from the four earlier experiments), then underadditivity might be expected. On the other hand, a suggested bottleneck model would account for R1 slowing in terms of response grouping, which predicts that S1 factors will have the *same* effect on R1 in the two task condition as they have on RTs for that task performed alone. This additive pattern was observed in the results of Experiment 5.

Various aspects of the data from the earlier experiments also converge to favor the grouping account. In the experiments with the short SOAs, there were strong trends for S2 factors to slow down R1 (which grouping requires); in these experiments, the correlations between R1 and R2 were also extremely high, reflecting low variability of interresponse times relative to the R1 and R2 times. In contrast, Experiment 3 with a longer SOA showed neither effect. Additionally, the R1s were elevated with the shorter SOAs, although the tasks were the same. Very similar patterns of times and correlations, implicating (although perhaps not proving) grouping, have been observed previously (Gottsdanker & Way, 1966).

The interpretation proposed here has implications for some general issues about the limitations on human information processing. First, the data provide converging evidence for the view that some encoding operations can take place without interference from other tasks the subject is occupied with at the time the stimuli are presented. This seems congenial to the view commonly expressed by proponents of automatic stimulus encoding, at least as this pertains to visual search.

Also, the results may have some bearing on the merits of the capacity approach to divided attention. A wealth of experimental evidence has demonstrated that subjects have substantial strategic control in dual-task situations, that is, that they can emphasize one task at the expense of another. This has led many to assume that "economic" notions like multiple pools of capacity, strategically allocated, may furnish an appropriate language for theories of divided attention (e.g., Navon & Gopher, 1979).

Taken most literally, this approach suggests that it is not the *control* of cognitive operations—that is, preparing them and scheduling them—but rather their *execution* that stretches the limits of the system. Studies manipulating stimulus factors with and without concurrent memory load appear to have fairly directly tested this idea, with negative results. Logan (1978) and Egeth, Pomerantz, and Schwartz (1977, November) found that stimulus factors increasing the difficulty of various stages interact *additively* with the memory load. Of course, it is possible (as suggested by Egeth et al.) that the memory load is not concurrent at all—that the subjects stop rehearsing it when the task is performed. The present experiments provide evidence against the capacity-depleted execution of these same stages in another situation for which capacity sharing has been suggested: the overlapping task paradigm. Like the memory load findings, this can be regarded as merely strategic: Subjects optionally choose not to share capacity in this situation but instead to proceed sequentially. However, concurrent memory, loads and overlapping tasks are prime examples of the sorts of situations for which capacity sharing was first proposed, and these converging results suggest that some doubts about it might be in order.

The existence of subject controlled trade-offs between tasks in dual-task paradigms might be accounted for in other ways. For instance, Logan (1978) and Gottsdanker (1980) suggest that an important locus of dual-task interference may be in *preparation* of the structures needed to perform the tasks. Strategic trade-offs may reflect different degrees of preparation for each task, rather than slowing in the actual cognitive operations composing the task. Reduction in preparation may be responsible for the costs of concurrent memory loads and also perhaps some portion of the R2 slowing observed earlier (e.g., the residual slowing observed at the longer SOA of Experiment 3). It is not clear what stage in the actual S-R sequence is lengthened by poor preparation, but the general fuel metaphor, which suggests a continuously divisible commodity, may be highly misleading. Thus, it might be the case that certain types of cognitive operations inevitably conflict and must be queued (e.g., response selection), whereas others sometimes proceed with little interference (e.g., encoding, response execution). However, preparation of a sequence of stages may require effort and time (less so after practice; see Logan, 1979), and thus be highly subject to strategic factors.

The present data by no means compel this general picture, but it is hoped that the present method, involving stimulus factor manipulations targeted to particular stages in temporally overlapping tasks, may play a useful role in the project of arriving at a detailed account of how cognitive tasks are combined in real time.

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