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Chronometric Evidence for Central Postponement in Temporally Overlapping Tasks

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When the stimuli from two tasks arrive in rapid succession (the overlapping tasks paradigm), response delays are typically observed. Two general types of models have been proposed to account for these delays. *Postponement models* suppose that processing stages in the second task are delayed due to a single-channel bottleneck. *Capacity-sharing models* suppose that processing on both tasks occurs at reduced rates because of sharing of common resources. Postponement models make strong and distinctive predictions for the behaviour of variables slowing particular second-task stages, when assessed in single- and dual-task conditions. In Experiment 1, subjects were required to make manual classification responses to a tone (S1) and a letter (S2), presented at stimulus onset asynchronies of 50, 100, and 400msec, making R1 responses to S1 as promptly as possible. The second response, R2, but not R1, was delayed in the dual task condition, and the effects of two S2 variables (degradation and repetition) on R2 response times in dual- and single-task conditions closely matched the predictions of a postponement model with a processing bottleneck at the decision/response-selection stage. In Experiment 2, subjects were encouraged to emit both responses close together in time. Use of this response grouping procedure had little effect on the magnitude of R2 response times, or on the pattern of stimulus factor effects on R2, supporting the hypothesis that the same underlying postponement process was operating. R1 response times were, however, dramatically delayed, and were now affected by S2 difficulty variables. The results provide strong support for postponement models of dual-task interference in the overlapping tasks paradigm, even when response times are delayed on both tasks.

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Human beings are plainly subject to severe limitations in their ability to perform more than one task at the same time. A sizable quantity of research has been directed toward characterizing and explaining these limitations. This goal is of both theoretical and practical importance. On the one hand, an understanding of these limitations will elucidate some very basic aspects of the architecture of human cognitive processing. On the other hand, such understanding should prove to be helpful in the rational design of complex systems requiring human-machine interaction, particularly those demanding rapid operator responses.

Restrictions in the ability to carry on multiple streams of mental computations may occur at a variety of levels, making the study of human attentional limitations a very broad area of research. A great deal of work has focused on processing limitations in perception and pattern recognition, and particularly the question of whether multiple familiar patterns can be identified in parallel. Most of this work involves a single coherent task, which requires processing many distinct, simultaneously presented stimuli. The present work deals instead with the larger problem of handling multiple *tasks,* each of which involves an unrelated mapping of a distinct set of stimuli to a distinct set of responses.

Research on dual-task interference has employed a variety of different experimental methods. Performance with continuous tasks extended over several minutes (such as analogue tracking of a moving stimulus) has been commonly investigated. Typically, such studies of continuous performance have looked at accuracy measures (such as RMS error) on tasks done alone or combined together (e.g., Wickens, 1983). This work has yielded many useful findings, but has not provided a theoretical understanding of the *causes* of dual-task interference in real time. The reason is that accuracy measures cannot discriminate between genuine simultaneous mental processing on both tasks and a strategy of switching back and forth between tasks while buffering stimuli and responses (Broadbent, 1982).

The emphasis in the present article will be on a different paradigm that offers a better opportunity to explore the real-time nature of dual-task interference, the *overlapping tasks paradigm.* In this paradigm, the subject is presented with two stimuli (S1 and S2) in rapid succession, and must make a response to each (R1 and R2, respectively) as rapidly as possible. This paradigm has sometimes been (prejudicially) labelled the psychological refractory period (PRP) paradigm, by analogy to the refractory period of individual neurons; we prefer a designation that leaves open the nature of any performance decrements.

The overlapping task paradigm was extensively investigated in the 1950s and 1960s, and a number of accounts were proposed (for reviews, see Bertelson, 1966, and Smith, 1967). It has been studied somewhat less of late, despite (or perhaps because of) the little agreement that was reached over the phenomena. This is unfortunate, as the paradigm potentially provides much more detailed information about the time course of dual-task interference than is obtained in the (currently more popular) continuous dual-task studies. The present article will attempt to demonstrate that when response times are collected in the overlapping tasks paradigm while selected experimental factors are manipulated, very strong constraints are imposed upon possible explanations of dual-task interference.

Approaches to Explaining Interference in Overlapping Tasks

Models of dual-task interference can be divided into two large categories: *postponement models* and *capacity-sharing models.* According to postponement models, interfence arises between two tasks because certain cognitive operations require a single mechanism to be *exclusively* dedicated to that operation for some period of time. When that mechanism is occupied in one task, processing stages in the other task that require the mechanism must be postponed until it becomes available—thus the concept of a processing bottleneck or single channel. Postponement models can be subdivided according to which stage(s) of processing are held to constitute the single-channel bottleneck. Proposals have included (1) *perceptual identification,* (2) *decision and response selection,* and (3) *response initiation and execution.* The early filter theory of attention (Broadbent, 1958) proposed that identification of stimuli was a bottleneck in the attentional system. The hypothesis that decision processes and response selection constitute a single-channel bottleneck was proposed by Welford (1952, 1980), and cogently defended by Smith (1967). More recently, a number of workers have argued that the primary source of interference does not arise until the initiation or execution of responses (Keele, 1973; Logan & Burkell, 1986; Norman & Shallice, 1985). The major alternative to postponement theories of dual-task interference has been variously labelled as capacity theory or resource theory (Kahneman, 1973; Norman & Bobrow, 1975; Wickens, 1983). Theories of this type suppose that no stage of any task requires *exclusive* access to a single mechanism, but rather that each task draws on limited resources that can be allocated among the tasks in a graded fashion. The efficiency of performance of each task is assumed to increase with the allocation of capacity, at least over a considerable range. The simplest version of this type of theory supposes that just a single very general resource is allocated to support all cognitive processes (Kahneman, 1973; McLeod, 1977b).

Evidence from the Overlapping Tasks Paradigm

According to the postponement model, some bottleneck stage(s) cannot operate simultaneously for each of the two overlapping tasks. This hypothesis yields the apparently straightforward prediction that as the stimulus onset asynchrony (SOA) between S1 and S2 is reduced, there should come a point at which any further reduction in the SOA produces a corresponding increase in the duration of R2 (measured from S2). The degree to which this famous "minus-one slope" prediction is borne out has been debated (see Bertelson, 1966; Kahneman, 1973; Kantowitz, 1974). It does seem to fit most data quite well, however, for overlapping choice-reactions.[1] Even where the minus-one slope prediction is confirmed, it is not very diagnostic, as it is also consistent with versions of capacity-sharing models (cf. McLeod, 1977b). And, of course, it cannot indicate where the locus of any postponement might be. It might seem that the postponement model should also predict that at relatively long SOAs, where the bottleneck stages in the two tasks would not overlap, dual-task R2 should be as short as the same R2 made in a single task alone. This has rarely been observed. However, a general cost of concurrent performance per se might be attributable not to specific task conflict, but rather to poorer preparation induced by the need to prepare two tasks in the dual-task condition. The suggestion that some dual-task slowing is attributable to such a factor has been suggested previously (Gottsdanker, 1980), and it is perfectly consistent with a single-channel bottleneck being the primary source of interference.

Another major finding that has frequently been observed with the overlapping/tasks paradigm is a slowing of the first response (R1) in the first task (Gottsdanker & Way, 1966; Herman & Kantowitz, 1970; Kahneman, 1973). R1 slowing is readily accounted for with capacity models, as both tasks are assumed to be performed with depleted allocations of capacity. Postponement models do not predict the slowing in any straightforward way, although the preparation factor noted above is one likely contributor. It has sometimes been suggested, however, that R1 slowing may result from a strategy called "grouping". The term "grouping", unfortunately, has several different meanings, all of which share the core idea that the two responses are coupled in some way. The term was used by Welford (1952) and Sanders (1967) to refer to a strategy in which the subject essentially treats S1 and S2 as a compound stimulus SI + S2 and selects a corresponding compound response R1 + R2. Borger (1963) suggested another possible type of grouping strategy: the first response is saved until the second response has been selected, so that the two responses can be emitted in rapid succession. We will call this form of grouping *conjoint responding.* If subjects voluntarily wait to emit R1 until R2 has been selected, a dramatic slowing of R1 would plainly result, regardless of whether or not the second task interferes directly with the first task. Both forms of grouping could account for R1 slowing without

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[1] Except that the function relating R2 to SOA rarely shows a sharp elbow; this is to be expected, given that the durations of all component stages undoubtedly have substantial variability.

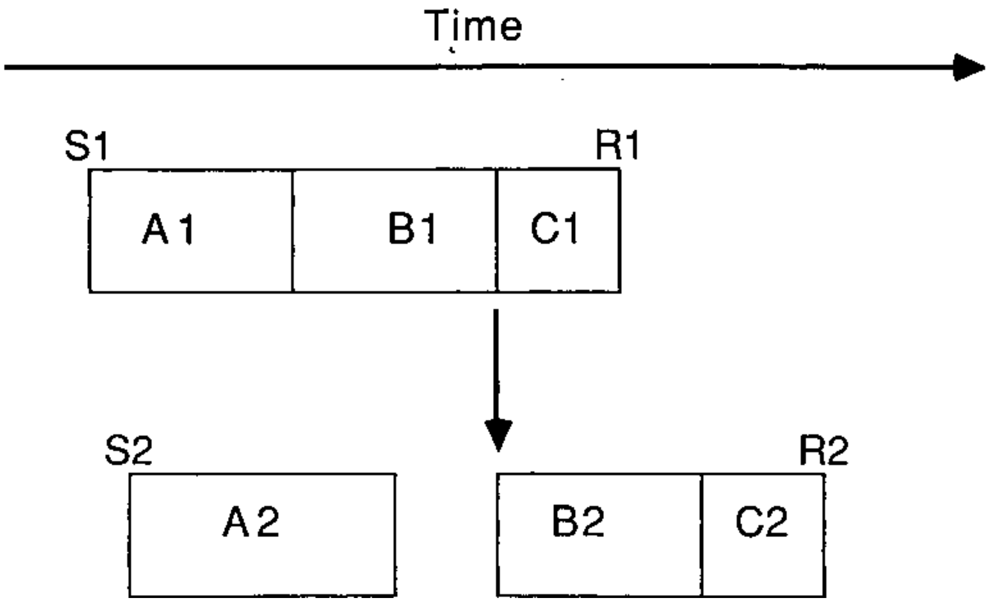

FIG. 1. A schematized stage model of overlapping tasks in which Stage B occupies a "single channel", whereas the other stages in both tasks can overlap without restrictions.

invalidating the postponement model. Thus, R1 slowing is, by itself, not especially diagnostic of the underlying causes of dual task interference.

A Chronometric Approach

As this brief overview of the overlapping tasks literature suggests, each of the main classes of models can provide a plausible account of the basic results. More decisive tests require more analytic experiments, deriving distinctive and non-obvious predictions from one of the model classes. Pashler (1984) developed a method for testing postponement models by manipulating task factors increasing the duration of selected stages of processing (following Sternberg, 1969). The logic is depicted in Figure 1. Assume for the moment, in accord with postponement models, that some crucial stage present in both tasks cannot be performed simultaneously and thus constitutes a single-channel bottleneck. This "bottleneck stage" (represented by B1and B2 of Figure 1) is both preceded (A1 and A2) and followed (C1 and C3) by other stages for which processing *can* proceed without interference. The various sub-varieties of postponement models differ, of course, in the claims they make about *which* processes comprise A, B and C.[2] Given this arrangement

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[2] The assumption that at least the earliest stimulus processing stages and the final stages of physical response execution do not constitute a bottleneck is reasonable, given the basic character of sensory and motor systems; thus the diagram can encompass the range of postponement possibilities. Note also that for present purposes it does not matter if any of the three stages hypothesized for each task is actually a composite of other isolable sub-stages. The reader will also note that the present analysis assumes that the same stages comprise the bottleneck in first and second tasks—this might be false, of course.

of processing stages, Task 2 will not generate any interference in Task 1, so we can write the equation for response times on the first task as simply

$$RT1 = A1 + B1 + C1 \tag{1}$$

It follows from the assumptions that Stage B2 will be postponed until the corresponding Stage B1 of the first task has been completed. We can therefore write the formula for RT2 as follows:

$$RT2 = \max(A1 + B1 + SW, SOA + A2) + B2 + C2 - SOA \tag{2}$$

The equation reflects the fact that Stage B2 cannot proceed until both (a) its input is available from completion of A2, and (b) the relevant processor is released, having completed stage B1 (note that we have, for completeness, included a term SW for whatever time might be required to switch the bottleneck processor from the first to the second task; in the figure, this is assumed to be zero). If the formulas as stated are combined with the (unrealistic) simplifying assumption of deterministic stage durations they yield the classic prediction of a — 1 slope relating RT2 to SOA at values of SOA small enough that $A1 + B1 + SW \geq SOA + A2$. In this case, Stage B2 is always waiting only for the processor to be switched over from Task 1. A flat slope is predicted at larger SOA values, where Stage B2 is always waiting for its input from Stage A2. If we adopt the more realistic assumption that stage durations have variability from trial to trial, then the "elbow" in the graph of mean RT2 against SOA will be smoothed out. Thus, observed slope values may never be as extreme as - 1, depending on whether there is a region where the probability of waiting for the input to Stage B2 is negligible.

Pashler's (1984) method for testing this version of the postponement model relied on experimental factors that selectively slow Stages A2 and B2. Consider first a factor that slows Stage B2, and compare its effect on RT2 in (a) the dual-task condition shown in the figure, and (b) a single-task control. Clearly, such a factor will slow RT2 the same amount in both the dual-task and single-task conditions. Stated generally: If a factor slows down stages of processing located at or beyond the locus of the single-channel bottleneck (i.e. at or beyond the stages postponed), it will have effects that are *additive* with the dual-task vs. single-task slowing.

Suppose, on the other hand, that we manipulate a factor that slows down Stage A2. In a single-task control, this slowing will be fully reflected in the RT. In the dual-task condition, however, Stage A2 is unable to begin until both its input and its processor are available, reflected in Equation (2) by the inclusion of the maximum of two random variables. The result is that some of the effects of the factor on Stage A2 will be "washed out" in RT2: on trials where Stage B2 is waiting on its processor and not its input, lengthening A2 will not increase RT2. The empirical principle can be stated generally: If a factor slows down stages of processing prior to the locus of the postponement, it will have effects that are *underadditive* with the dual-task vs. single-task slowing. Together, these two principles provide a way of determining which stages, if any, are subject to a single-channel bottleneck. These principles can be seen as relatively simple cases of PERT networks, whose applications have been analysed in some important contributions of Schweickert (Schweickert, 1978; Schweickert & Boggs, 1984). Schweickert (1980) proposed a related analysis of another kind of dual task situation, but analysed it rather differently from the approach taken here.

The methods utilized here demonstrate that postponement models may make entirely non-obvious predictions, offering powerful opportunities for experimental tests. Overadditive interactions in latencies are overwhelmingly more common than underadditive interaction (and also follow straightforwardly from capacity theories, cf. McLeod, 1977b), making underadditivity predictions especially diagnostic for testing postponement models.[3]

Pashler (1984) reported preliminary studies using the methodology just sketched. Subjects performed two classification tasks that involved visual inputs and manual responses; the tasks were done singly and in a dual-task condition with a fixed SOA. The first task required a two-way classification of a single visual stimulus, and the second task required visual search of a number of elements, with a target presence/absence decision. A stimulus intensity factor that would be expected to affect early visual processing (see, e.g., Miller, 1979) in Task 2 (the search task) was found to be *underadditive* with dual task slowing. The factor of target presence/absence in the search task, which would be expected to affect the central stages of decision and/or response selection, had effects that were *additive* with dual-task slowing. These results are consistent with a postponement model, assuming a single-channel bottleneck subsequent to processes affected by stimulus intensity but prior to processes affected by target presence/absence. A bottleneck in the decision and/or response selection stages would fit this pattern of results very naturally.

The results reported by Pashler (1984) are suggestive, but, as he noted, they fall short of providing conclusive evidence for the central bottleneck version of the postponement model for several reasons. First of all, postponement models make a strong prediction that factor effects at stages prior to the bottleneck should become progressively smaller at shorter SOAs. As SOA shortens, the wait for the processor becomes progressively longer, and the proportion of trials on which delay in early stimulus processing of S2 will

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[3] Note that relaxation of the idea of the strict successiveness of the stages (McClelland, 1979) would lead only to a quantitative not qualitative change in the predictions. However, this relaxation may be unnecessary in many cases, as the empirical evidence currently available suggests that a discrete transition between stimulus evaluation and response selection is a reasonable approximation to reality (Meyer, Yantis, Osman, & Smith, 1984).

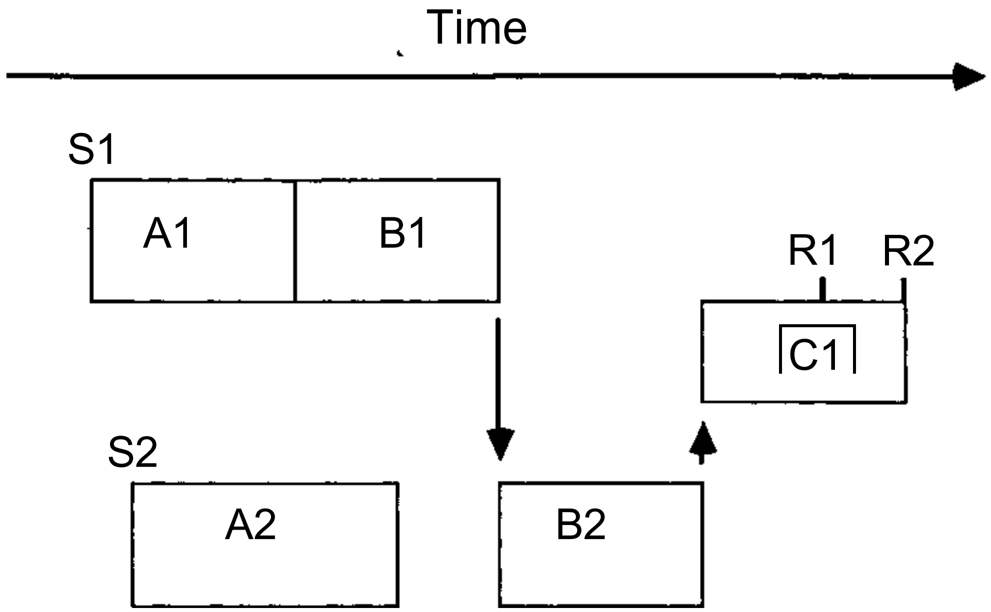

FIG. 2. Stage B postponement, with grouping of the variety first described by Borger (1963): a common response execution stage begins after both responses are selected, and executes R1 and R2 in rapid succession.

have any effect on RT2 progressively decreases. Pashler (1984) employed only a single SOA and therefore could not test this prediction. In addition, the target presence/absence variable employed in those studies may have effects not confined to decision and/or response selection (Pashler & Badgio, 1985).

R1 Effects and their Interpretation

A more troubling aspect of the results reported by Pashler (1984) was the behaviour of RT1, the time for responding in the first task. In the dual-task condition, RT1 was clearly elevated and was, furthermore, affected by the S2 difficulty factors. These factors delayed dual-task RT1 approximately one half as much as they delayed dual-task RT2. Pashler (1984) favoured the explanation that subjects engaged on about half of the trials in the conjoint-responding version of the grouping strategy, mentioned above. In Figure 2 this conception of grouping is diagrammed. The proposed sequence of processes differs from that shown in Figure 1 in that a common stage of response execution C' operates *after* both responses are selected; this common response execution stage produces both R1 and R2 in rapid succession. If we represent the time taken by the common process C' to produce the two responses as C'1 and C'2, we can state the following equations for dual-task response times with the conjoint-responding grouping strategy:

$$RT1 = \max(A1 + B1 + SW, SOA + A2) + B2 + C'1 \quad (3)$$

$$RT2 = \max(A1 + B1 + SW, SOA + A2) + B2 + C'2 - SOA \quad (4)$$

According to this model, on any given dual task trial, the only contributor to the difference in RT1 and RT2 will be differences in the durations of stages C'1 and C'2, the times for the conjoint-response process to execute the two responses. Thus one should expect extremely high positive correlations across trials between RT1 and RT2. High correlations were in fact observed by Pashler (1984). Substantial positive correlations might arise for other reasons, however, so competing explanations are not ruled out by this observation. The grouping explanation for R1 slowing was rather ad hoc, and a primary purpose of the present research is to test some specific predictions of the grouping account.

The Present Experiments

The goals of the present experiments are (1) to provide stronger tests of the postponement model of dual-task interference that assumes a central processing bottleneck (in decision and/or response selection stages), especially by systematically varying SOA; (2) to conduct tests of the model with a more appropriate set of tasks; and (3) to conduct planned empirical tests of the conjoint-responding grouping explanation for R1 dual-task slowing. We employ two classification tasks, one mapping single tones to manual responses and the other mapping single letters to a different set of manual responses (made with the other hand). We test the effects of two second-task variables that ought to have their primary effects on different stages in the second task: stimulus identification and response selection. The magnitude of these effects is examined for both RT1 and RT2 in the dual-task condition and also for RT2 on the second task performed alone. We did not include Task 1 single-task blocks because those data are of lesser interest, and we find that each additional within-subject instructional condition imposes substantial burdens on subjects and decreases the stability of performance. The central-bottleneck version of the postponement model predicts a specific pattern of underadditivities and additivities with dual-task slowing. Specifically, a variable affecting early stimulus processing is predicted to have dramatically reduced effects on RT2 in the dual-task condition, whereas a variable affecting response selection is predicted to have very similar effects in single- and dual-task conditions. The shortening of the SOA between S1 and S2 is predicted not only to lead to the usual increase in RT2, but also to increase the degree of underadditivity of the early S2 factor. Manipulation of a variable affecting the duration of response selection is predicted to be *additive* with SOA, on the other hand, as it should affect Stage B2 in

Equation 2, beyond the wait for the bottleneck processor to become available.

Finally, we examine the grouping issue directly, by introducing an instructional manipulation: in Experiment 2, we encourage R1 slowing. If the instructional manipulation works by producing grouping on top of the hypothesized bottleneck, then, on the basis of Equations (3) and (4), a distinctive and surprising pattern of results for Experiment 2 should emerge: (1) R1 times should be dramatically elevated due to R1 being held back until the central processing on Task 2 is finished; (2) the variability in interresponse intervals (IRIs) between R1 and R2 across trials should be substantially reduced, yielding very high correlations between RT1 and RT2; and (3) as the S2 factors manipulated are hypothesized to affect terms that contribute in exactly the same way to Equations (3) and (4), these second-task factors should slow RT1 the same amount as RT2. If grouping is completely suppressed in Experiment 1, on the other hand, R1 times should not vary with SOA, and they should be unaffected by S2 difficulty factors.

The hypotheses being tested thus make the non-obvious prediction that the pattern of factor effects on dual-task RT2 should be essentially *unchanged* by the grouping strategy. This prediction can easily be confirmed by comparing Equations (2) and (4), in which the same terms for the manipulated stages appear, combined in the same way. What conjoint-response grouping does is make the execution of R1 contingent on the completion of the central processes (decision and response selection) for R2 as well as those for R1. Therefore, if the hypothesis is correct, the pattern of underadditive and additive effects involving different S2 factors, as evidenced in RT2, should be unchanged by the introduction of grouping. The grouping strategy will, however, tie R1 responses to R2 responses, in terms of both absolute R1 latencies and the pattern of factor effects.

The two S2 variables employed in these experiments are the visual intensity of S2, and repetition of S2 from the previous trial. There is ample evidence locating latency effects of intensity in the duration of perceptual processing (e.g. Miller, 1979). Repetition of S2 necessarily involves repetition of the stimulus, the response, and the stimulus-response mapping from the previous trial; thus, a priori, one might suspect it of having effects anywhere from early sensory processing all the way to motor behaviour. However, the major effects of repetition appear to arise in the central process of response selection—i.e. the mental process that negotiates the mapping between stimulus codes and response codes. Repetition has been shown to interact with S-R compatibility (Bertelson, 1963; Kornblum, 1969), and with the number of alternative response choices (Biederman & Stacy, 1974; Kornblum, 1975). Repetition does not interact with visual quality in visual choice reaction time (Hansen & Well, 1984). Furthermore, Ells & Gotts (1977) and Smith (1968) found that when the response is repeated but the stimulus is not, no speedup is observed.[4] Additional evidence for a response-selection locus of the repetition variable, internal to the data of Experiment 2, will be discussed below.

EXPERIMENT 1

The first experiment employed two easy choice-response tasks. In the first task, subjects classified an auditory tone as high-pitch or low-pitch, indicating their response by pressing one of two keys, using the left hand. In the second task, subjects classified a single letter as an A, a B, or a C, indicating their response by pressing one of three keys, using their right hand. Two S2 variables were examined: stimulus intensity and stimulus repetition.

Method

Subjects. Thirty-six undergraduates at the University of California, San Diego, participated as subjects in the experiment, in partial fulfilment 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). The letters presented measured about 0.4 cm in width by 0.4 cm in height and were viewed from a distance of approximately 60 cm. The characters were presented on a black background either in white (for the high-intensity) or in grey (for the low-intensity) displays. This difference corresponded to about 1.5 log units of intensity reduction.

Design. The experiment was divided into 8 blocks of 54 trials each. Two of these eight blocks were single-task blocks, in which the subject responded to S2 (the letter) only. The remaining six blocks were dual-task blocks: the

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[4] The following simple and informal account of this pattern of repetition effects appears to provide a satisfactory gloss on a wide range of results. Between the sensory stimulus and the emitted response a succession of internal codes is activated; some of the pathways between these codes are highly overlearned, such as the pathway between the stimulus S and the corresponding letter-identity code, or the pathway between a certain spatially directed movement intention and the execution of the corresponding button press response. Other pathways are assembled just for the task at hand, such as the connection between the internal letter code and the internal spatial code for the response. These "routes" are assembled so as to take maximum advantage of the existing overlearned pathways. However, it is just these arbitrary pathways that have been assembled on an ad hoc basis that benefit so substantially from repetition; by contrast, the overlearned pathways show minimal effects of repetition. Of course, this is really just a special case of a very robust generalization in human learning and memory: that the degree of strengthening of a trace varies inversely with its prior strength (see, e.g., Woodworth & Schlosberg, 1954).

subject responded to both S1 (a tone) and S2 (a letter). In each block, half of the letter stimuli (S2) were presented at low intensity and half at high intensity. Each of the three SOAs—50, 100, and 400 msec—was used equally often. Each block of 54 trials thus consisted of 9 trials from each of the six cells formed by combining SOA and S2 intensity, presented in random order. The repetition factor was not constrained in any way: on each trial, the letter was chosen randomly (with replacement), independent of other factors.

The order in which single-task and dual-task blocks were presented was counterbalanced as follows: Equal numbers of subjects were randomly assigned to four groups. For the first group, the single-task blocks were 1 and 5; the other blocks were dual-task blocks. For the second, third, and fourth groups, the single-task blocks were, respectively, 2 and 6, 3 and 7, and 4 and 8.

Procedure. The subjects were given instructions in writing describing the task. The instructions stressed that both responses should be made as rapidly and accurately as possible, but emphasized that subject should "respond as rapidly as possible to the first stimulus." Prior to data collection, each subject worked through 144 practice trials, in 4 mini-blocks of 36 trials each. One of these blocks was a single-task block. During practice, the experimenter emphasized to the subject the importance of making the first response as promptly as possible.

Each trial began with the presentation of a plus sign as a fixation point. The fixation point appeared at the centre of the display for 1000msec, and 200 msec after its offset the tone (S1) was presented. The tone, at either 300 or 900 Hz, was presented for 33 msec. After an SOA of 50, 100, or 400 msec, a single letter (A, B, or C) appeared in the centre of the screen. The subject responded to S1 by pressing either the "z" or "x" key on the keyboard, corresponding, respectively, to a low or a high tone, using the first or the second finger of the left hand. The subject responded to S2 by pressing the "m", "," or or "." key on the keyboard, corresponding to "A", "B" or "C", respectively, using one of the first three fingers of the right hand. As soon as the second response was detected by the computer, the display was terminated. In the single-task blocks, the sequence of stimuli was exactly the same, except that no response was required to the first stimulus. If an error was made on either task, a message indicating the task with the error was displayed. The error message blinked for 2 sec, preceded by 200msec of blank screen and followed by 600 msec of blank screen. The intertrial interval between completion of one response and presentation of the fixation point for the next trial was 1.8 sec. At the end of each block the subject rested until he or she felt ready to resume. At this time, feedback was provided for the block just completed for the first (emphasized) task only (mean correct latency).

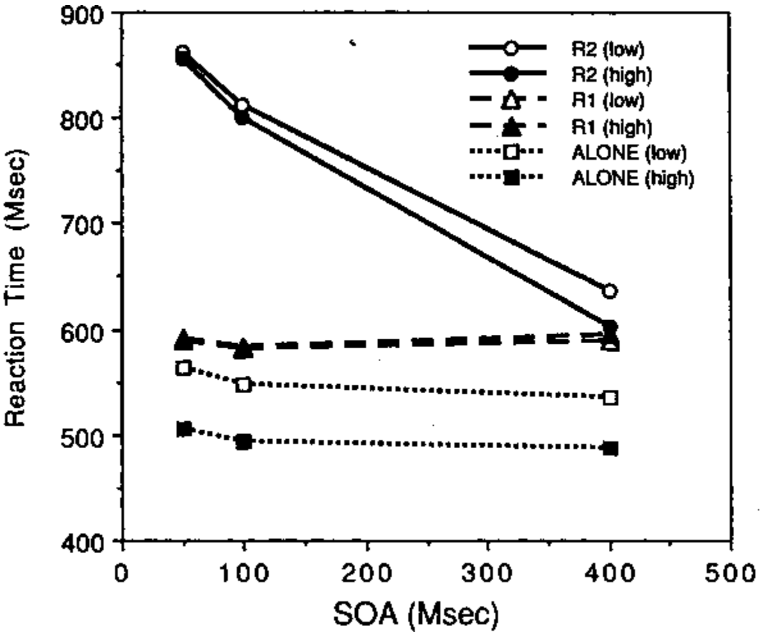

FIG. 3. The effect of intensity (high versus low) on RTs in Experiment 1. Alone = second task performed in isolation.

Results

Response times under 200msec, or in excess of 1500msec, were discarded. Figure 3 presents subjects' mean RTs for correct[5] responses, as a function of task, SOA and intensity (shown as low and high). Figure 4 presents the corresponding results as a function of task, SOA, and S2 repetition.

Basic RT Effects

An analysis of variance was performed on the RT1 dual response times, including as factors SOA, S2-intensity, and S2-repetition. None of these factors affected RT1 significantly [SOA:$F(2, 70) = 1.3, p > 0.25$; S2-intensity: $F(1, 35) = 0.2, p > 0.25$; S2-repetition: $F(1, 35) = 2.4, p > 0.10$]. It is especially to be noted that mean R1 times were remarkably flat across SOA's (50: 591 msec; 100: 583msec; 400: 593msec). Thus the present experiment appears to have succeeded in emphasizing Task 1 sufficiently to avoid the common finding of RT1 slowing with greater task overlap (shorter SOA).

Secondly, an analysis of variance was performed on RT2 response times, including as factors task (alone vs. dual), SOA, S2-intensity, and S2-repetition. RT2 was significantly longer for dual task than alone,

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[5] Other analyses of the data were conducted using more stringent cutoffs (e.g. 1200 msec), or discarding all data from trials in which *either* reponse was in error (rather than only discarding data from the task with the error). The results were unchanged.

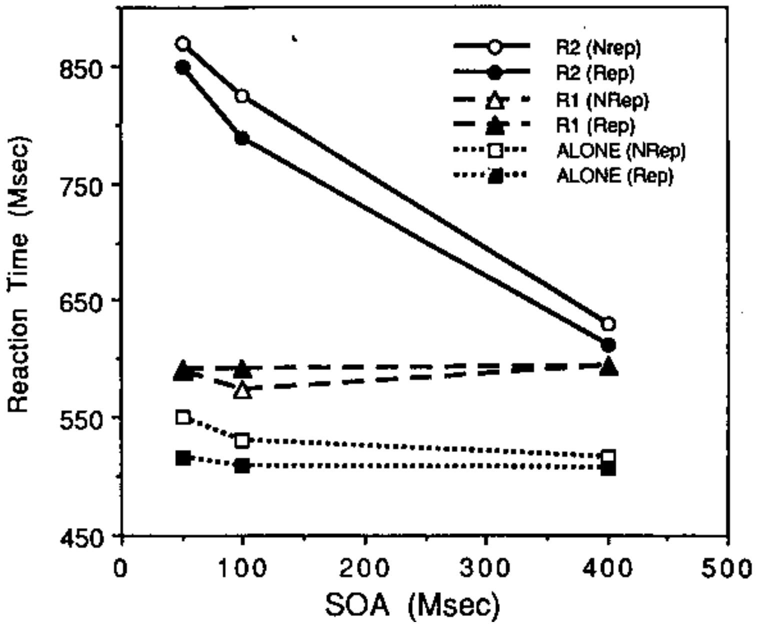

FIG. 4. The effect of S2 repetition (Rep = repeated; NRep = non-repeated) on RTs in Experiment 1. Alone = second task performed in isolation.

$F(1, 35) = 114.8$, $p < 0.001$, for low S2 intensity trials, $F(1, 35) = 64.7$, $p < 0.001$, and for non-repeated-S2 trials, $F(1, 35) = 26.0$, $p < 0.001$. SOA had a highly significant effect, $F(2, 70) = 379$, $p < 0.001$, and the effect of SOA was significantly larger on RT2 dual than on RT2 alone: Task x SOA, $F(2, 70) = 267.0$, $p < 0.001$. For the RT2 dual condition the mean response times for each SOA, averaged over intensity and repetition factors, were 859, 806, and 621 msec, for SOAs of 50, 100, and 400, respectively. The slope of the first measured segment from SOA 50 to SOA 100 was - 1.06. This is very close to the — 1 slope that would occur according to postponement models if over this SOA range Stage B2 always waits for the processor to shift from Task 1 rather than waiting for completion of Stage A2 that provides its input.

Predicted Factor Interactions

As shown in Figure 3, the effect of intensity was greater for RT2 alone (53msec), than RT2 dual (17msec); for Task x Intensity, $F(1, 35)= 19.4$, $p < 0.001$. The intensity effect was reduced as SOA decreased for RT2 dual, but not for RT2 alone: the Task x SOA x intensity interaction was just significant, $F(2, 70) = 3.2$, $p < 0.05$.

The effect of repetition did not differ significantly for the RT2 dual (25msec), compared to the RT2 alone (21msec): Task x S2-repetition, $F(1, 35) = 0.4$, $p > 0.25$. The repetition effect also did not vary significantly with SOA, $F(2, 70) = 2.1$, $p > 0.10$. There was a marginally significant trend toward a Task x SOA x S2-repetition interaction, *F*(2, 70) = 2.5, $0.05 < p < 0.10$, reflecting the greater modulation of the S2 repetition effect by SOA for RT2 alone. This trend, if real, is puzzling, as the only effect of SOA on RT2 alone that appears relevant to the repetition effect is to increase only slightly an already rather long interval from the occurrence of the repeated stimulus.

Finally, intensity and repetition did not interact, *F*(1, 35) = 0.14, $p > 0.25$, confirming, according to standard additive factors logic, that these two factors did not affect common stages (Sternberg, 1969). This also replicates the observations of Hansen & Well (1984) and provides support for the assumption that intensity directly affects only Stage A2 (Fig. 1), and repetition only Stage B2. This assumption, of course, was used to derive the predictions of the postponement model in the introduction. None of the remaining interactions approached significance.

Error Rates

Table 1 shows the average error rates as a function of task, SOA, S2-intensity, and S2-repetition. An overall analysis of the error rates was performed, including as factors task (R1 vs R2-alone vs R2-dual-task), SOA, S2-intensity, and S2-repetition. The effect of task was significant, *F*(2, 70) = 12.5, $p < 0.001$, reflecting a higher error rate for R2 dual. The effect of SOA was also significant, *F*(2, 70) = 3.7, $p < 0.03$. The interaction of Task x SOA was significant, *F*(4, 140) = 8.8, $p < 0.001$. These last two effects reflect an unexpected increase in errors at the long SOA (400 msec) for R2 dual. The only explanation of the excess errors that we have to suggest is that this SOA required producing both the longest inter-response interval (IRI), and the longest intervals between S1 and R2; some subjects may have occasionally felt self-imposed deadlines as a function of these durations, and responded hastily on a small percentage of trials. Additionally, the effect on error rate of repetition of S2 was significant, *F*(1, 35) = 9.0, $p < 0.005$, as was the interaction of Task x S2-repetition, reflecting the fact that the S2-repetition effect appeared predominantly in the R2-dual error rates.

TABLE 1 Percent Errors: Experiment 1

	TASK		
SOA	*R1*	*R2(dual)*	*R2(alone)*
50	4.2	4.8	3.4
100	3.4	4.4	3.0
400	2.5	8.2	3.7

R1-R2 Correlations

For each subject separately, the correlation between RT1 and RT2 dual across trials was computed (including only trials on which both responses were correct and lay within acceptable cutoff bounds). Separate correlations were computed for each subject at each SOA, and the resulting numbers were then averaged across subjects. The mean correlations thus computed were 0.78, 0.80, and 0.64, for SOAs of 50, 100, and 400msec, respectively.

Discussion

The results of Experiment 1 match the predictions derived from the postponement model with a bottleneck at the central stages of decision and/or response selection (Pashler, 1984; Smith, 1967; Welford, 1952, 1980). The specific results consistent with this model (essentially, Figure 1) were as follows:

1. RT1 was not affected significantly by any of the variables manipulated in the experiment.
2. The effect of S2 intensity was strongly underadditive with the slowing of RT2 caused by performing it dual-task rather than alone.
3. The effect of S2 intensity on RT2 dual was smaller at shorter SOAs.
4. The effect of S2 repetition on RT2 was approximately additive, with the slowing caused by the dual-task condition.
5. The trial-to-trial correlation between RT1 and RT2 was significantly greater than zero, but well below 1.0.

These results support the model illustrated in Figure 1, according to which dual-task slowing is caused by postponement of a stage of the processing of S2 that is at or before the point where S2 repetition has most of its effects, but after the point where S2 intensity has most of its effects. The experiments would thus seem to have achieved two of the main goals set forth in the introduction. First the postponement model has been applied to a pair of tasks that is more appropriate for basic research in the overlapping tasks paradigm than those originally studied by Pashler (1984). The tasks used were a pair of relatively standard speeded multi-choice classification tasks; this is a type of task for which a simple, but fairly general stage analysis has credibility, and for which factors can be identified that will very plausibly influence key stages selectively. Second, we have derived a rather complex set of predictions, including how factor effects should interact with SOA, and verified these predictions within a single coherent set of data. Furthermore, appropriate instruction of the subjects has produced a data set without any effect of degree of task overlap (influenced by SOA) on RT1. The RT1 slowing in Pashler's (1984) data required additional grouping assumptions to be reconciled with the predictions of postponement models.

EXPERIMENT 2

The results of the first experiment provide support for the postponement model (Pashler, 1984; Welford, 1980) with a bottleneck in central processing (decision and/or response selection). This model is specifically supported for a combination of choice response-time tasks under conditions in which the first task is emphasized, and R1 is to be made as quickly as possible. The strongest support for the alternative class of capacity-sharing models in the overlapping-tasks paradigm has come from the common finding of a slowdown on R1 under dual-task conditions. Perhaps the postponement model is correct for experiments in which fast responses on the first task are stressed, but a capacity-sharing model is correct for task combinations where emphasis on fast first-task responses is less severe. But another alternative, proposed by Pashler (1984), is that even when R1 slowing does arise, the postponement model still applies, but subjects are sometimes following a strategy of response grouping of the conjoint-responding type (Figure 2). According to this strategy, subjects wait until the decision and response selection processes are complete for both tasks before emitting the two responses in rapid succession. When subjects follow this strategy, the applicable postponement model follows equations (3) and (4) rather than (1) and (2) in the introduction.

Pilot work suggested that the behaviour of RT1 could be controlled fairly well by subjects with appropriate instructions. The second experiment therefore repeated the procedure of the first experiment with no changes whatsoever except in the instructions, which now encouraged subjects to delay R1 and produce the two responses close together in time. The goal of the second experiment was to examine the complex pattern of factor interactions that are predicted by the conjunction of the postponement model and the assumption of conjoint-responding type of grouping. As discussed in the introduction, the pattern of factor interaction involving RT2 dual should be unaffected. The changes to be expected from Experiment 1 are an overall slowdown in RT1 dual, the emergence of a pattern of factor effects and interactions for RT1 dual similar to the pattern for RT2 dual, and an increase in the positive correlation between RT1 dual and RT2 dual across trials. On the other hand, if R1 slowing typically reflects capacity sharing, then the invitation to delay R1 should result in major changes in the pattern of results, with disappearance of the patterns of results indicating response-selection postponement.

Method

The apparatus, stimuli, design, and procedure were the same as Experiment 1, except as noted overleaf.

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

Procedure. The written instructions were as in Experiment 1, except that they encouraged subjects to produce the two responses in a "nice orderly rhythm" (although it was emphasized that the first response must precede the second).

Results

The results from one of the subjects were discarded due to extraordinarily high error rates. Response times under 200 msec, or in excess of 1500 msec, were discarded as before. Figure 5 presents subjects' mean RTs for correct responses, as a function of task, SOA and S2 intensity. Figure 6 presents the corresponding results as a function of task, SOA, and S2 repetition.

Basic RT Effects

First, an analysis of variance was performed on the R1 response times, including as factors the SOA, S2-intensity, and S2-repetition. The effect of SOA was significant, $F(2, 76) = 91.9$, $p < 0.001$, reflecting a dramatic increase in RT1s with lengthening SOA (746, 755, and 866msec for SOAs of 50, 100, and 400, respectively). The effect of S1-intensity was significant,

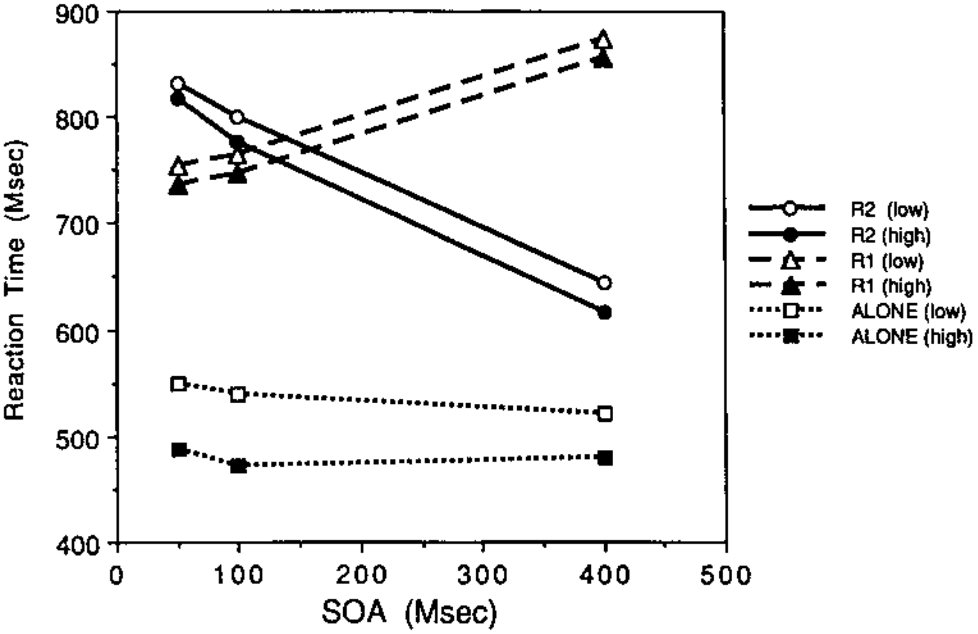

FIG. 5. The effect of intensity (high versus low) on RTs in Experiment 2. Alone = second task performed in isolation.

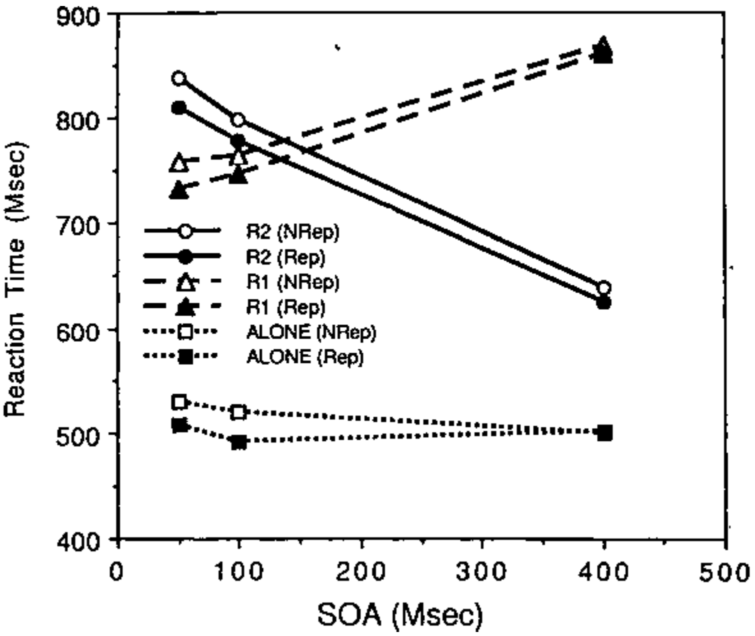

FIG. 6. The effect of S2 repetition (Rep = repeated; NRep = non-repeated) on RTs in Experiment 2. Alone = second task performed in isolation.

F(1, 38) = 6.7, $p < 0.01$, reflecting a 19-msec difference. Finally, the effect of S2 repetition was significant, *F*(1, 38) = 17.2, $p < 0.001$, reflecting an 18-msec difference.

Secondly, an analysis of variance was performed on RT2, including as factors task (alone vs. dual-task), SOA, S2-intensity, and S2-repetition. RT2 was significantly slower for dual task than alone, *F*(1, 38) = 257.1, $p < 0.001$, for low-intensity S2 trials, *F*(1, 38) = 20.0, $p < 0.001$, and for non-repeated S2 trials, *F*(l, 38) = 21.4, $p < 0.001$. SOA had a significant effect, *F*(2, 70) = 249.6, $p < 0.001$, and the effect of SOA was larger on dual-task RT2 than on R2 alone: Task x SOA, *F*(2, 70) = 201.8, $p < 0.001$. For the RT2 dual condition, the mean response times averaged over intensity and repetition were 825, 789, and 632msec for SOAs of 50, 100, and 400, respectively. The slope of the first measured segment from SOA 50 to SOA 100 was 0.726.

Predicted Factor Interactions

As Figure 5 suggests, the effect of intensity was greater for RT2 alone (58msec) than R2 dual (22msec): for Task x intensity, *F*(1, 38) = 15.9, $p < 0.001$. The figure also suggests that the intensity effect was reduced as SOAs decrease for RT2 dual, but not RT2 alone. This trend was again significant: for Task x SOA x intensity, *F*(2, 76) = 3.3, $p < 0.05$. The effect of repetition was apparently not reduced in the RT2 dual (20 msec), compared to the RT2 alone (16msec): Task x S2-repetition, *F*(1, 38) = 0.4, *p* > 0.25. The repetition effect did, however, vary significantly with SOA, *F*(2, 76) = 5.9, *p* < 0.005. None of the remaining interactions was significant.

Error Rates

Table 2 shows the average error rates as a function of task and SOA. An overall analysis of the error rates was performed, including as factors task (RT1 vs. RT2 alone vs. R2 dual), SOA, S2-intensity, and S2-repetition. The effect of task was significant, *F*(2, 76) = *9.1, p* < 0.001. The effect of SOA was not significant, *F*(2, 76) = 0.8, *p* > 0.25. The interaction of Task x SOA was not significant, *F*(4, 152) = 1.2, *p* > 0.25. The effect of intensity was significant, *F*(1, 38) = 7.3, *p* < 0.01. Finally, the effect of repetition was significant, *F*(1, 38) = 6.1, *p* < 0.02. No other effects were significant.

TABLE 2 Percent Errors: Experiment 2

	TASK		
SOA	*R1*	*R2(dual)*	*R2(alone)*
50	3.7	4.0	2.1
100	3.5	3.7	2.4
400	3.4	5.0	2.5

R1-R2 Correlations

The mean correlations, computed as in Experiment 1, were high across all SOAs: 50msec: 0.94; 100msec: 0.94; 400msec: 0.89.

Discussion

The basic results of Experiment 2 again match the predictions derived from the postponement model (Pashler, 1984; Welford, 1952, 1980), assuming a bottleneck in the central stages of decision and/or response selection. Specifically, and as in Experiment 1:

1. The effect of S2 intensity was severely underadditive with the slowing of RT2 caused by performing it in the dual task condition rather than alone.
2. The effect of S2 intensity on RT2 dual was reduced as SOA decreased.
3. The effect of S2 repetition on RT2 was approximately additive with the dual-task slowing of RT2.

In this experiment the instructions were designed to invite subjects to engage in the grouping strategy of the conjoint-responding variety, superimposed on the postponement, if such a strategy is in fact readily available, as hypothesized earlier. Results 1-3 are indicative of postponement and thus consistent with this account. Alternatively, if delayed R1s were generally produced by capacity sharing, then our instructions should have encouraged that strategy instead, and the evidence for postponement should have been quite absent. Thus, the results suggest that an invitation to delay R1 does not produce signs of capacity-sharing but, instead, evidence of central postponement. However, the experiment provides much stronger tests of the grouping plus postponement account, and these tests hinge on three important results, which differ from those of Experiment 1:

4. The RT1 dual now increased dramatically as SOA increased.
5. The RT1 dual was now clearly affected by the S2 factor manipulations, to approximately the same degree as the RT2 dual.
6. The correlations between RT1 and RT2, which were substantial in the previous experiment, are now extremely high.

Each of these results was expected from the analysis illustrated in Figure 2. The results also provide converging evidence for our analysis of the repetition effect. We have been assuming (for reasons detailed in the introduction) that the effect is on the duration of response selection, but it would be quite damaging to the present analysis if the effects were actually on response execution itself. In that case, the results would be consistent with a postponement of this execution stage. However, the fact that the effect on R2 latencies is now mirrored in the R1 latencies makes such a possibility most unlikely. It seems rather bizarre to suppose that subjects would delay R1 on non-repetition trials in anticipation of the fact that the execution of R2 would be slightly slower!

In summary, Experiment 2 provides evidence that an invitation to delay R1 and produce it in close temporal proximity to R2 does not eliminate the basic postponement at the decision or response selection stage. Rather, subjects react by coupling the motor responses, so that the first response also awaits the completion of the postponed stage of selection of the second response. The account proposed by Pashler (1984) that the commonly observed slowing of R1 may reflect the emergence of this strategy, by some subjects or on some trials, acquires new plausibility. Of course, optimal confirmation of this conjecture would now be provided by evidence indicating that when subjects are *not* provided with any particular instructions regarding interresponse timing, the resulting performance does in fact reflect the mixture of two types of trials that the present account would lead one to expect.

GENERAL DISCUSSION

The overall results of the present experiments strongly confirm the basic predictions derived from assumptions of the postponement model, with a bottleneck in central processing (decision and/or response selection), supplemented by the assumption that, under certain conditions, subjects engage in the strategy of conjoint-response grouping (selecting responses for both tasks before emitting either). The prediction most critical for the postponement model was that the factor of dual-task slowing (relative to a single-task control) would be underadditive with S2 intensity but additive with S2 repetition. It was further predicted that the instructions favouring or discouraging grouping would not alter these predicted interaction trends. It was expected, however, that these instructions would dramatically change the timing of R1 and that instructions to group would cause R1 to be delayed by the S2 factors in the same manner as R2. The pattern of factor effects actually observed is summarized in Figure 7. The figure represents (collapsed over SOA) the magnitude of the effect of the two factors visual intensity (INT), and S2 repetition (REP), for the two instructional conditions favouring grouping (group) and discouraging grouping (nogroup). As the figure shows, the effect of intensity on RT2 was dramatically reduced in the dual-task condition, compared to the single-task condition. The effect of S2 repetition was approximately additive with the RT2 dual task slowing. These patterns were essentially unchanged by the type of grouping instruction. What instructions did dramatically alter was the magnitude of S2 factors

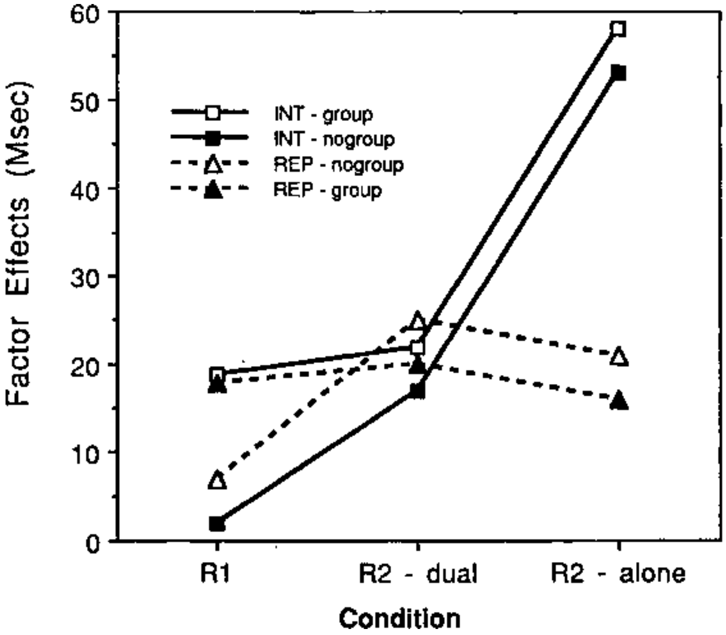

FIG. 7. The magnitude of the effects of intensity (INT) and S2 repetition (REP) on RTs in Experiment 1 (nogroup) and 2 (group), observed in R1, R2 dual-task and R2 alone (single-task).

effects on RT1. When the instructions favoured grouping, RT1 showed factor effects comparable in magnitude to those shown by RT2 in the dual-task condition. This effect was predicted from the hypothesis that with grouping of the conjoint-responding variety, R1 execution is delayed until after the postponed central stage of Task 2 (Stage B2; see Figure 2 and Equation 4). Thus whatever factors influence Stage B2 should have their effects "pushed" onto RT1 as well.

The present interpretation of the effects of the grouping instructions is strongly supported by several other aspects of the data. The conjoint-responding grouping model asserts that subjects select responses for both tasks and then emit them in rapid sequence. If so, one would expect R1 and R2 to be emitted with close to a fixed relative timing. Two specific aspects of the data support this prediction. First, one can look at the correlation in timing of R1 and R2, which measures how well they stayed together across trial-to-trial variations in timing. In fact, the correlation between R1 and R2, which was only moderately high in Experiment 1, was, under the grouping instructions of Experiment 2, extremely high. A second analysis can be made of the extent to which the mean interresponse interval (IRI) between R1 and R2 remained unaffected by the asynchrony in presentation of S1 and S2. The IRIs, which under the no-grouping instructions of Experiment 1 varied widely with SOA (318, 323, and 427 msec for SOAs of 50, 100, and 400 msec, respectively), were little affected by SOA under the grouping instructions of Experiment 2 (129, 134, and 167msec for SOAs of 50, 100, and 400msec, respectively).

General Implications and Directions for Further Research

The results presented here lend strong support to the postponement model with a bottleneck at the central stages of decision and/or response selection. This conception of dual-task interference, originally developed by Welford (1952) and Smith (1967), was broadly consistent with the pattern of early results reviewed by Bertelson (1966) and Smith (1967), but the evidence available at that time provided relatively weak constraints on theorizing. The present evidence, summarized above, provides more compelling support for postponement theory.

The present data also bear strongly on the major alternative class of models for dual-task interference, general capacity theory (McLeod, 1977b). This model leads naturally to the prediction that dual-task slowing of RT2 (due to diversion of capacity) should interact *overadditively* with factors that increase the difficulty of the second task (i.e. the amount of work to be done). McLeod (1977b) provides a formal graphical analysis leading to this conclusion, but for present purposes a simple physical analogy should be sufficient. Suppose we have 3 workers shovelling dirt who can each shovel 1 ton/hour, and the task consists of shovelling 6 tons of dirt. Time to completion will be 2 hours. If we diverted one worker away (reducing capacity), the time to completion would increase by 1 hour: if, instead, we added 6 more tons (increase task difficulty), the time to completion would increase by 2 hours. But if we simultaneously added 6 more tons *and* diverted away one worker, the time to completion would go up by 4 hours, not merely the 3 hours that would be the sum of the separate effects. This is an overadditive interaction pattern. The similar logic on which capacity theory is based thus does not provide a natural explanation for the data pattern we found, where dual-task slowing had underadditive and additive effects with second-task difficulty factors, depending on which factor was involved.

The strongest motivation for general capacity models has been the commonly observed slowing of the first response in the overlapping task paradigm. As described in the introduction, response grouping provides an alternative interpretation of such RT1 dual-task slowing. Using instructions designed to promote a grouping strategy (Experiment 2), we verified a number of predictions derived from a specific version of the grouping hypothesis (conjoint responding). As the grouping hypothesis corroborated in this experiment, together with the postponement model, can also explain RT1 dual slowing, that phenomenon now provides no support for capacity theory.

Logically speaking, of course, these results do not show that *all* RT1 dual-task slowing is due to response grouping in all possible task combinations with all possible instructions. It might be that capacity sharing is simply a strategy that was not elicited in either of the present instructional conditions. In Experiment 1, we may have promoted a strategy in which the first task received a full complement of capacity. In Experiment 2, we promoted the delay of R1. If general capacity sharing were a strategic option available to the subject, then it would seem that this invitation to delay R1 would have promoted the strategy, either with or without a grouping process similar to the conjoint-responding strategy. In either case, the results should have looked quite different than they did. Thus, the factor effects do not support general capacity-sharing models: these models have no apparent way to predict the pattern of underadditive and overadditive interactions that the response selection postponement model successfully predicted in the current results.

There are several directions in which the approach to studying human dual-task performance adopted here can be extended. On the one hand, it might be possible to develop a detailed quantitative model of the stage durations underlying the effects observed here. In principle, there ought to be a number of quantitative dependencies in the data, beyond those evaluated here, which could be examined in the course of formulating a complete quantitative model. Another important topic for future research is the generality of the present findings. It is worth emphasizing that it is an open question how far the conclusions reached in this article regarding response selection postponement will generalize beyond the conditions investigated. Quite possibly, the results may depend on the use of two *manual* responses. As noted above, there have been many suggestions that the choice of input and response modalities can have major effects on the magnitude of dual-task interference (e.g. Allport, Antonis, & Reynolds, 1972). This may well be correct, but the published evidence that supports this idea is not very conclusive (e.g. compare McLeod & Posner, 1984, and McLeod, 1977a). It may also be worth noting that interference might depend upon sharing of response modalities, as alleged, but still have its proximal cause in response selection postponement. For instance, the postponement could be programmed in advance in order to prevent potential crosstalk, which would otherwise create problems in the case of a shared modality of response. This kind of possibility illustrates an important but often overlooked point: that evidence that an interference effect depends upon response modality does not show conclusively that dual-task slowing situation is actually caused by postponement of response *execution.* Another obvious and important question concerns the degree to which the pattern of interference observed in tasks like those studied here will change with practice. Ordinary introspection might suggest that practice enables unlimited parallel processing, but laboratory work is inconclusive here as well: the oft-cited cases of so-called "automaticity" either involved tasks like holding onto memory loads, which probably do not involve actual simultaneous response selection, and/or they did not include latency measures capable of discriminating between genuine parallel processing and switching between tasks.

In summary, the generality of the decision and/or response-selection bottleneck revealed here remains an important area for research, and findings reported to date are inconclusive. Of greater importance, however, is the possibility that the methodology developed in the present article may prove useful in exploring in detail the "real-time" basis for dual-task interference in a wide variety of experimental situations.

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