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Bottlenecks in planning and producing vocal, manual and foot responses

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Abstract

When subjects perform two sensorimotor tasks (T1 & T2) close together in time, T2 response selection is often delayed. Five experiments examined whether T2 response selection waits for both selection and execution of the response in T1. In the first two experiments, T1 required a sequence of vocal responses (R1). When the sequence length in R1 was increased, R1 took longer to complete (unsurprisingly); however, the (manual) second response (R2) was little affected, and R2 usually occurred while the R1 sequence was underway. Similar results were found when T1 involved a sequence of vocal responses and T2 required a foot movement (Experiment 3). However, when R1 was a manual sequence, and R2 involved either manual or foot movements, R2 was substantially delayed, and usually occurred after R1 was completed. When T1 required arm reaching, variability in reaction time (but not movement time) was associated with slowing of R2. The results argue for (1) a central bottleneck that does not include response production and (2) a separate response-production bottleneck specific to production of manual or foot responses (and likely to play no role in usual dual-task laboratory experiments).

Introduction

When people try to perform more than one task at nearly the same time, the speed or accuracy of their performance is often impaired (dual-task interference). The simplest form of dual-task interference is observed when subjects are presented with two stimuli (S1 and S2), separated by a variable stimulus onset asynchrony (SOA), and attempt to produce a response to each stimulus (R1 and R2, respectively) as quickly and accurately as they can. Even when the tasks seem cognitively trivial, response time for the second task (RT2) increases as the SOA is shortened. This slowing of RT2 is usually referred to as the psychological refractory period or PRP effect (Vince, 1949; Welford, 1952; Bertelson, 1966; Smith, 1967a). The present research uses the PRP paradigm to explore dual-task interference in the production of response sequences, with the goal of learning more about the relationship between cognitive limitations and motor-control limitations.

Recent evidence implies that a fundamental cause of dual-task interference (as observed in the PRP effect) is the fact that central processing (decision, response selection, and possibly response initiation) generally requires the exclusive involvement of a single mental mechanism[1] (see Pashler, in press, for a review). The result is a bottleneck in the PRP task: while task 1 uses the mechanism, the operations that require the mechanism in task 2 are forced to wait (Welford, 1952; Pashler, 1984), thereby delaying task 2. One kind of evidence for this bottleneck comes from experiments that have manipulated the duration of particular stages of processing in the second task. Bottleneck

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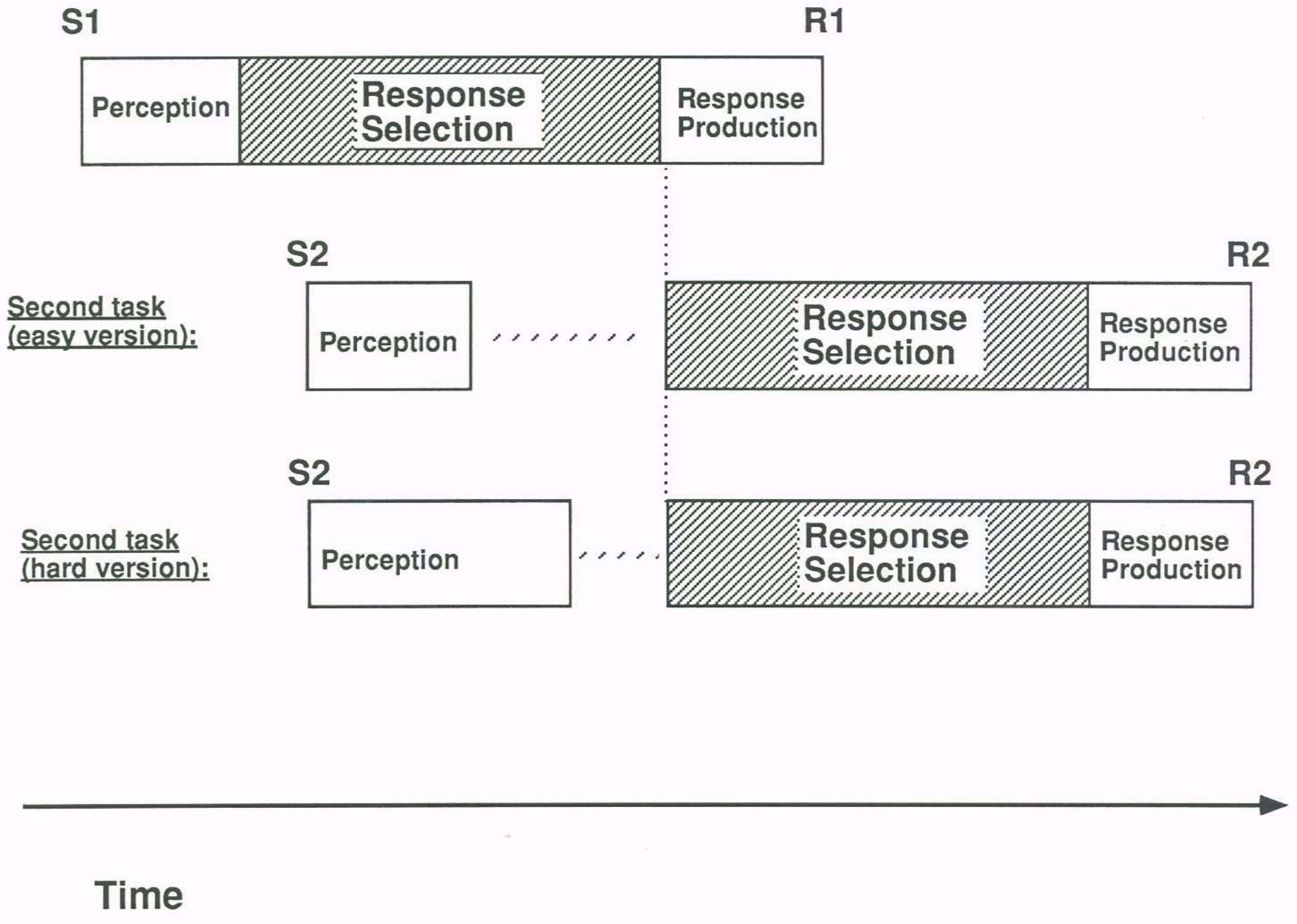
[1] Obviously, the term mechanism is used in the broad sense: it needn't be localized anatomically, and the bottleneck might be the result of inhibitory interactions among different sets of machinery.

models make distinctive predictions for the results of such experiments. When stages of processing in task 2 that occur before the bottleneck-dependent stage are slowed down and the SOA is short, R2 should still occur at approximately the same time (Figure 1 A), whereas at long SOAs R2 should be slowed. The bottleneck model therefore predicts an underadditive interaction between SOA and factors affecting the duration of pre-bottleneck stages. This interaction occurs because the effect of the factor is "absorbed" while processing in the second task waits for the bottleneck to be freed up. By contrast, any variable that slows the processing at the bottleneck stage itself adds a constant to RT2, regardless of SOA (Figure 1B). In short, pre-bottleneck manipulations in task 2 should interact underadditively with SOA, while bottleneck and post-bottleneck manipulations are additive with SOA.

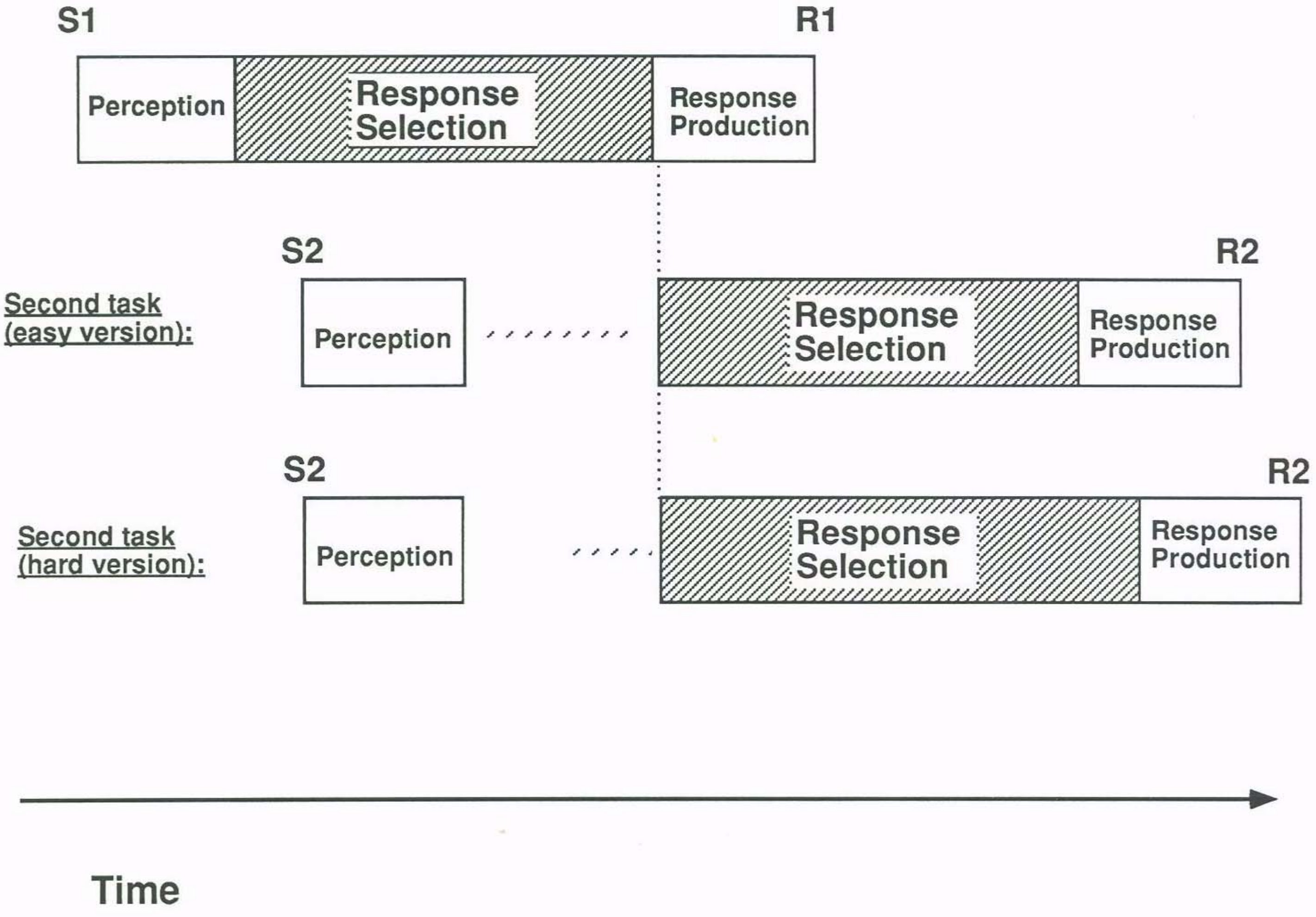
An analogy may help make these predictions more intuitive. If one walks into a bank immediately after another customer, and there is only a single teller on duty, the teller will represent a bottleneck: one will not leave the bank as soon as one would otherwise have (analogous to the PRP effect). However, since the teller is the bottleneck, there is no need to walk quickly - small differences in walking time will be absorbed, leaving the total time one spends in the bank unaffected. On the other hand, once one reaches the teller, taking extra time will increase total time spent in the bank.

*** INSERT FIGURE 1A & 1B***

Experiments using this sort of logic have manipulated factors that slow the perceptual processing in task 2, and observed the interactions predicted by a post-perceptual bottleneck (Pashler, 1984; Pashler & Johnston, 1989). On the other hand, variables slowing response selection in the second task (e.g., S-R compatibility) generally have the same effect on RT2 in the dual and single task conditions, and these effects do not change with SOA (Pashler, 1984; Pashler &



1A. The sequence of processing stages in two tasks. Time is from left to right, the first task takes S1 to R1, the second task takes S2 to R2. Response selection (shaded) cannot operate in two different tasks at the same time. There are two versions Task 2 : easy and hard, differing in the duration of the response selection. The effect does not delay R2 (when the SOA is short, as in the figure) .



1B. The same model makes different predictions when response selection is made difficult: RT2 is now lengthened correspondingly.

Johnston, 1989; McCann & Johnston, 1992; Fagot & Pashler, 1992). This pattern of results implies that response selection in task 2 must be part of the bottleneck.

Is Response Execution Subject to Bottlenecking?

The simplest model consistent with these results would postulate a bottleneck that encompasses response selection and claim that response execution plays no part in this bottleneck. Response selection in task 2 waits for the completion of response selection of task 1, on this view, while other stages (including execution) can overlap with each other or with response selection. (The assumption that perceptual processes in task 2 begin as soon as S2 is available is supported by additional observations beyond those mentioned, including the fact that accuracy in tasks requiring visual search of brief masked displays is almost unaffected by temporal overlap with another task; Pashler, 1989.)

There are several alternatives to this simple view, however. At the other extreme, one could propose a single central bottleneck that includes both response selection and response execution. (Response execution is taken here to include whatever central processes are involved in taking the output of the response selection stage and generating appropriate commands to the muscles. Obviously, it is only the central response execution processes that could plausibly be part of the bottleneck, since it's hard to see how T2 could be delayed by peripheral activity in the motor system which operated under open-loop control.) On this view, then, response selection in T2 would not commence until central motor-control machinery had issued commands to the muscles to produce R1. Another account would postulate two separate bottlenecks: one in selection of responses and another in production of responses. On this view, selection in one task would have to wait for selection in another task, and production in one task would wait for production in another, but selection in one task could overlap production in another task.

Possibilities like those just described -- which would include response production in bottleneck(s) -- are consistent with results of the laboratory PRP studies generally interpreted as favoring a response selection bottleneck. The findings described above involving manipulations of response selection duration imply that response selection (but not perceptual analysis) in task 2 is delayed by task 1. They also rule out the idea that producing the second response is the only operation in task 2 that is subject to delay (as proposed by Keele, 1973, and Norman and Shallice, 1985, among others). However, they do not provide any information at all about what stages of the first task are being waited for by the second task. Previous studies of dual-task interference directed specifically at uncovering interference with response execution have typically used one task as a "probe" measure of "capacity demands", and the relationship between performance of two responses has gone unexamined. For reasons to be described in the General Discussion, these studies cannot distinguish the different accounts of dual-task interference with response execution, either.

The goal of the present studies is to explore this issue by looking at performance in two overlapping tasks while manipulating variables associated with response execution in one task. The specific strategy involved varying the duration of response execution in task 1 of a PRP situation, and determining how RT1 and RT2 are affected. The basic logic is as follows: If a central bottleneck encompasses response selection and execution in task 1, then increasing the time for this process will delay not only R1 but also task 2 response selection, at short SOAs. At long SOAs, on the other hand, task 2 will not be affected. Therefore, a bottleneck in selection and execution predicts an overadditive interaction in RT2 between factors slowing response-execution and SOA. On the other hand, if the bottleneck does not encompass response execution, slowing task-1 response execution should obviously affect only task 1, regardless of SOA.

Previous PRP Studies Manipulating Task-1 Variables

In addition to the task-2 manipulations described earlier, the literature also contains several PRP studies that involve task-1 manipulations. These studies would seem to bear on the question at hand, but they too leave the main question unanswered. In several of these experiments, the difficulty of "cognitive" stages of task 1 was manipulated. For example, Smith (1969) varied the number of alternatives in a one-to-one choice first task. This factor - number of alternatives -- mostly affects the duration of response selection (Sternberg, 1969). The effects propagated onto RT2 just as one would predict from a bottleneck that encompassed response selection, Note, however, that this propagation would be predicted whether or not the bottleneck also encompassed response execution. Broadbent & Gregory (1967) and Pashler (1984) also found that various decision-related task 1 factors slowed task 2 responses at least as much as they slowed task 1 itself. These results confirm that task 2 response selection waits for task 1 response selection, but they don't say whether it waits for response selection alone, or for response selection plus additional mental operations in task 1 (such as response execution).

Several studies attacked the question of what role response production plays in the PRP effect by using a go-no-go response in task 1. For example, Smith (1967b) required subjects to press a button when a disk was on one side of fixation, and to make no response when the disk was on the other side; task 2 required a vocal choice response to a visual S2. Different subjects showed very different patterns of results, but on average the PRP effect was reduced by about one-third when the first task did not require a response. Smith assumed that both go and no-go trials required a "decision component", while only the go trials involved a "motor component." She therefore concluded that the "single channel extends to the motor component as well (p. 351)." Similar observations were made by Bertelson and Tisseyre (1969), who also found great variability between subjects.

Recent findings point out certain problems for such interpretations, however. For example, detecting a pre-specified target in visual search doesn't seem to involve the central bottleneck (Pashler, 1989), which makes it plausible that non-targets in search tasks could also be rejected without this mechanism. On the other hand, it is also possible that no-go stimuli might trigger selection (and even, in some sense, execution) of "null" or inhibitory responses. Therefore, fact that RT2 is delayed more after go compared to no-go task 1 trials (Smith, 1969) could be reconciled with any account about the role of response execution mechanisms in the PRP effect. The go/no-go task seems inherently ambiguous.

Present Experiments: Manual and Vocal Response Sequences

In principle, there are many kinds of motor behaviors and many different response-execution variables that might be investigated using the PRP logic sketched above (manipulating task 1 response execution time). The present investigations focus primarily on production of sequences of vocal or keypress responses. Sequences of keypress and vocal responses can be produced without visual guidance, and they represent a behavior with substantial practical significance. Furthermore, previous research has led to some useful information about the operations involved in response production in such sequences.

The specific question considered in most of the experiments described below is how increasing the number of elements in the task 1 response sequence affects the start and finish of R1, and especially how it affects RT2. Sequence length has been a popular variable in experiments studying motor programming (e.g., Henry & Rogers, 1960; Sternberg, Monsell, Knoll and Wright, 1978; Klapp, Abbott, Coffman, Greim, Snider & Young, 1979). When the response is prepared in advance, as in simple RT, sequence length effects are usually much smaller than when the response is not prepared in advance, as in a choice task (Klapp et al, 1979). One interpretation -- suggested by Klapp and his colleagues -- is that when the response is known in advance, motor programming can be taken care of before the production of the sequence begins (thus producing the larger sequence effects with choice responses. On the other hand, Sternberg, Knoll, Monsell and Wright (1988) suggested that even when the sequence is known in advance, an intermittent and cyclical motor-programming process occurs after the movements have begun, with programming occurring prior to the command generating each succeeding element in the sequence. Their model was able to predict the rather subtle effects of sequence length on the time to begin producing a pre-planned sequence, and on the duration of each element of the sequence. In summary, effects of sequence length on time to begin a response are generally attributed to motor programming operations, with opinions varying as to whether motor programming is necessary with pre-planned response sequences. This issue will not be critical for the present experiments, which will focus mostly on the effects of sequence length on time to complete a sequence in cases where the identity of the response sequence is not known in advance.

Specific Preliminary Hypotheses

Let us return to the question of what happens when a PRP experiment requires someone to produce a sequence of responses in the first task, and consider different possible sources of dual-task interference in more detail. In the situations to be considered, different stimuli call for different T1 sequences. As noted above, one possibility is that the central bottleneck encompasses only response selection (Figure 2A). Response selection in task 1 outputs an abstract specification of the desired sequence (Pashler & Baylis, 1989; Wallace, 1971), on this view, and subsequent response programming and response execution processes proceed in parallel with the first task[2]. If selection takes the same amount of time regardless of sequence length, then RT2 should not be affected by this variable. Task 2 should be delayed by task 1 response selection (the PRP effect), but the degree of delay should be independent of sequence length. On this model, motor programming and/or execution may take longer for longer sequences, but this variable will affect task 1 and not task 2.

*** INSERT FIGURE 2A, 2B, 2C, 2D ***

A second hypothesis is that the bottleneck encompasses not only response selection but also a stage of response programming which occurs <u>between</u> response selection and response execution, and which takes more time the greater the response complexity (Figure 2B). In this case, effects of sequence length should affect the time to begin R1 (regardless of SOA) and propagate onto task 2 when the SOA is short (with the maximal propagation equal to the effect on RT1). One could construct a number of different versions of this hypothesis which would share the idea that response programming in task 1 is part of the bottleneck.

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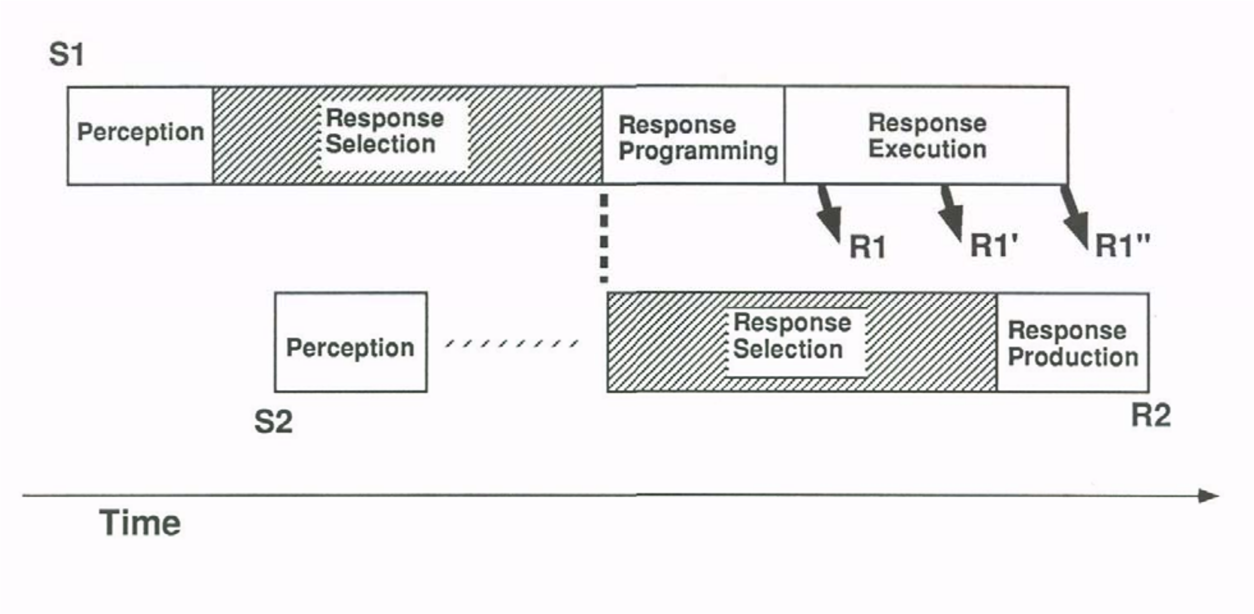
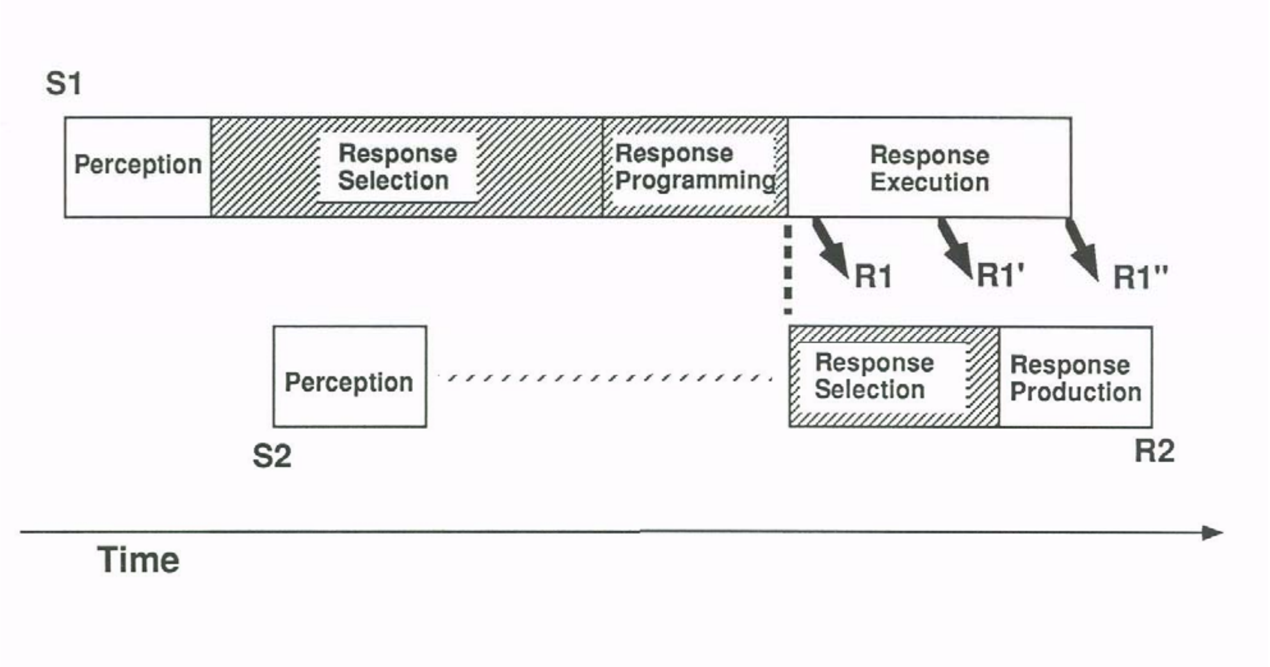
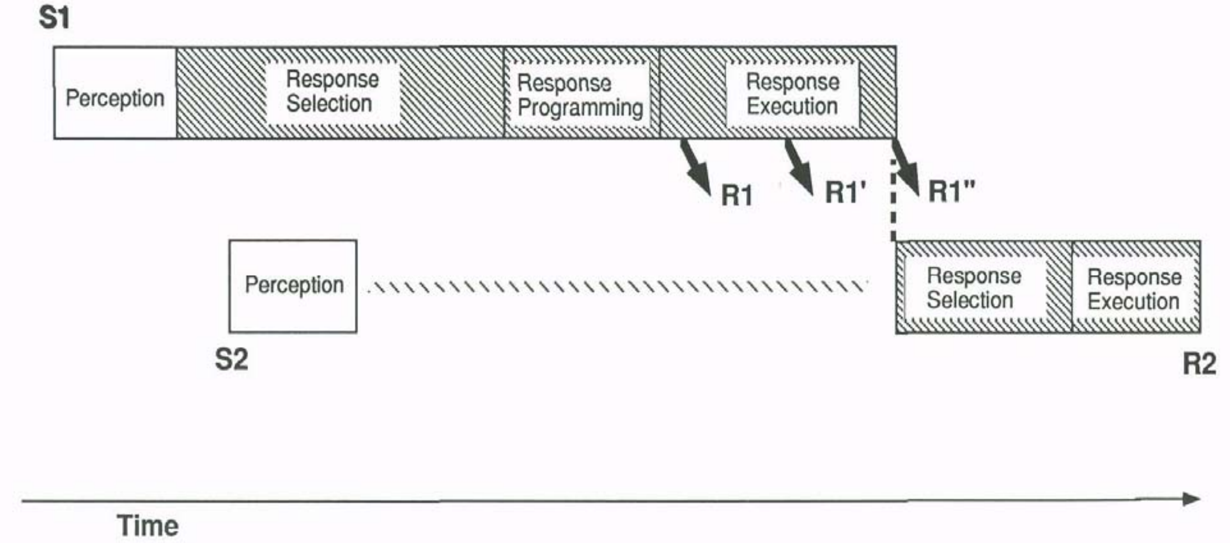
[2] For simplicity, the stages of response production in the second task are not broken down.



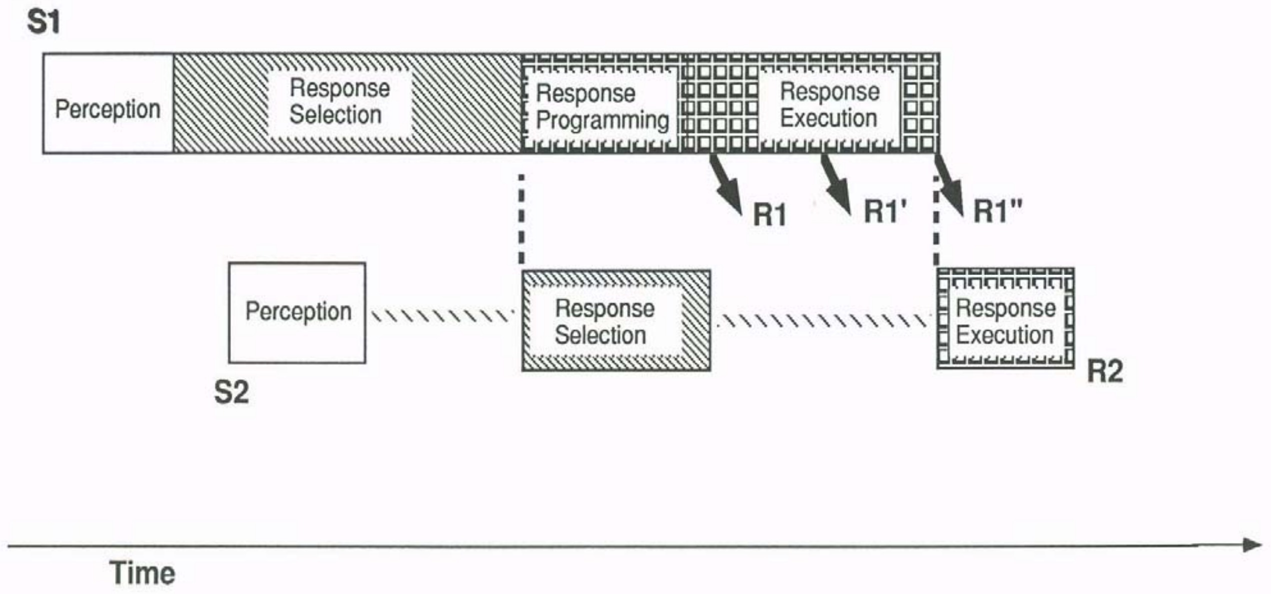
2A. A response selection bottleneck, with response programming and execution <u>not</u> part of bottleneck.



2B. Bottleneck encompassing response selection and programming



2C. Bottleneck encompassing response selection, programming <u>and</u> execution.



2D. Two bottlenecks: one in response selection, the other in programming and execution.

On both the first and second hypotheses, one would expect that the effects of sequence length on the time to complete R1 would not be propagated onto RT2. A third hypothesis would predict that effects on completion time would propagate, however. According to this hypothesis, the bottleneck encompasses response selection, programming and execution (Figure 2C). Suppose, for example, motor programming operations occur prior to the production of each element of the sequence (as Sternberg and his colleagues have argued). If this motor programming occupies the bottleneck mechanism until it is completed, then lengthening the R1 sequence should slow RT2 to approximately the same degree it slows the completion of the R1 sequence rather than the start of it.

Finally, a fourth possibility is that there are two bottlenecks - one in selection and the other in production (Figure 2D). Like the previous model, this predicts that lengthening the R1 sequence should slow RT2 to the same extent it slows completion of R1. It can be readily distinguished from the other model, however, by means of slightly more elaborate experiments, which be discussed below.

These are not the only possibilities that could be constructed, but it will be sufficient to have them available to refer to in considering the results of the experiments that follow.

Experiment 1

In the first experiment subjects performed two speeded choice tasks. In the first task, subjects saw a digit "1" or "5" on a computer monitor (S1) and responded by saying either "one" or "one two three four five", respectively (R1). Thus the identity of the digit (1 vs. 5) served as the manipulation of R1 sequence length, and this factor was randomized within a block. In the second task, subjects heard a tone (S2) and pressed one of two response keys (R2), depending on its pitch. Subjects were instructed to try not to let their responses on task 1 be delayed by the dual-task situation; given that constraint, they were instructed to make R2 as rapidly and accurately as possible.

Method

Subjects

Twenty one undergraduate students at the University of California, San Diego participated in a single-session experiment in partial fulfillment of a lower division course requirement. (An additional seven subjects performed two sessions of the same experiment, and their data will be discussed briefly below).

Apparatus and Stimuli

The stimuli were presented on NEC MultiSync monitors, controlled by IBM PC microcomputers. The first stimulus was one of two digits, a 1 or a 5, drawn in white on a black background. The characters measured approximately 1.5 cm in height (1.43 degrees visual angle based on a typical viewing distance of 60 cm). The second stimulus was a tone presented through the speakers in the monitor at either 300 or 900 Hz. Subjects spoke through a microphone which was plugged into a Gerbrandts Model G1341T voice-activated relay. The relay was in turn connected to the computer. The equipment was adjusted for each subject to insure that the voice could be picked up (but not the sound of keypresses.)

For each trial, the time at which the vocal responses began and ended was recorded (these will be termed R1 start-time and R1-end-time. respectively). The R1 -end-time was the first point after sound ceased which was not followed by any additional sound for at least 800 ms; pilot work showed this was ample time to detect completion of the verbal response. It was not possible to score the accuracy of the vocal responses, but pilot data disclosed that individuals in this population could count from one to five essentially without error.

Design

The experiment was divided into 8 blocks of 48 trials per block. There were two factors: SOA (50, 150, and 850 ms) and complexity of response to S1 (the word "one" or the series of words "one two three four five"). There were a total of 6 possible trial types (3 SOAs X 2 R1 complexity levels), each of which occurred 8 times per block. The order of trials was randomized for each block.

Procedure

The subjects were given instructions that described the task, and they were reminded to respond both as quickly and as accurately as possible. Subjects were told not to delay the first task response, to articulate each word loudly, and to avoid slurring the words together. Immediate feedback for each trial was not given, but the number of R2 errors and the average reaction times for both R1 and R2 were presented at the end of each block. Subjects rested after each block, and pressed a key when they were ready to resume.

Each trial began with a 750 ms presentation of a plus sign in the center of the screen as a fixation point. Two hundred fifty ms after its offset, S1 (the digit "1" or "5") was presented in the center of the screen, where it remained until the subject responded to both S1 and S2, unless they failed to respond within 3500 ms, in which case the trial was considered an error. If the subject responded faster than 150 ms the trial was considered an error as well. Following an SOA of 50, 150, or 850 ms from the onset of the digit, S2 (one of two tones, 300 or 900 Hz) sounded for 150 ms. The subject responded to this tone by pressing the key on the alpha-numeric keypad labeled "H" for a high tone or "L" for a low tone (the H and L keys were the quotation and slash, respectively, depressed with the middle and index finger on the right hand, respectively.) The intertrial interval between the final response and the onset of the fixation point for the next trial was 2 seconds.

Results and Discussion

Any RTs below 150 ms, RT2s or RT1 start times that exceeded 1800 ms, or RT1 end times that exceeded 3000 ms, were discarded as deviant (for most subjects, this rejected no trials or just a few trials.) Figure 3 shows the mean RTs to start and complete the R1 (vocal) response, and the manual RT2, all as a function of SOA and R1 complexity (counting to 1 vs. counting to 5).

*** INSERT FIGURE 3***

The time to begin the vocal R1 was not significantly affected by complexity: for counting to one (henceforth, R1-start-time(1)) was 499 ms, and for counting to five (R1-start-time(5)) was 513 ms, F(1,20)=2.9, p>.10, MSe=2172. The effect of SOA was also not significant, F(2,40)=2.2, p>.10, MSe=2633. The interaction of these two factors was also nonsignificant, F<1.

The R1-end-time was, obviously, affected by R1 complexity: R1-end-time(5) was 1332 ms, while R1-end-time(1) was 720 ms. This difference was significant, F(1,20)=133, p<.001, MSe=88873. The effect of SOA was not significant, F(2,40)<1, nor was the interaction of R1 complexity by SOA, F(2,40)=1.6, p>.20, MSe=5432.

The RT2 (manual second-task response) was 747, 690 and 531 ms for SOAs of 50, 150 and 850 ms, respectively. This PRP effect was significant, F(2,40)=69, p<.001, MSe=7618. The second response was slower overall when R1 was counting to five (RT2(5) = 704 ms) than when R1 was counting to one (RT2(1) = 608). This main effect of R1 complexity was significant, F(1,20)=16, p<.001, MSe=18430. The interaction of R1 complexity and SOA was nonsignificant, F<1. R2 error rates were .06 for R1 complexity 1, and .04 for R1

3. Mean RTs for Experiment 1 as a function of SOA. RT1-S and RT1-E are latencies to start and end first-task response; RT2 is latency for second-task response. (1) and (5) refer to the complexity of the first task (one vs. five element response sequences, respectively.)

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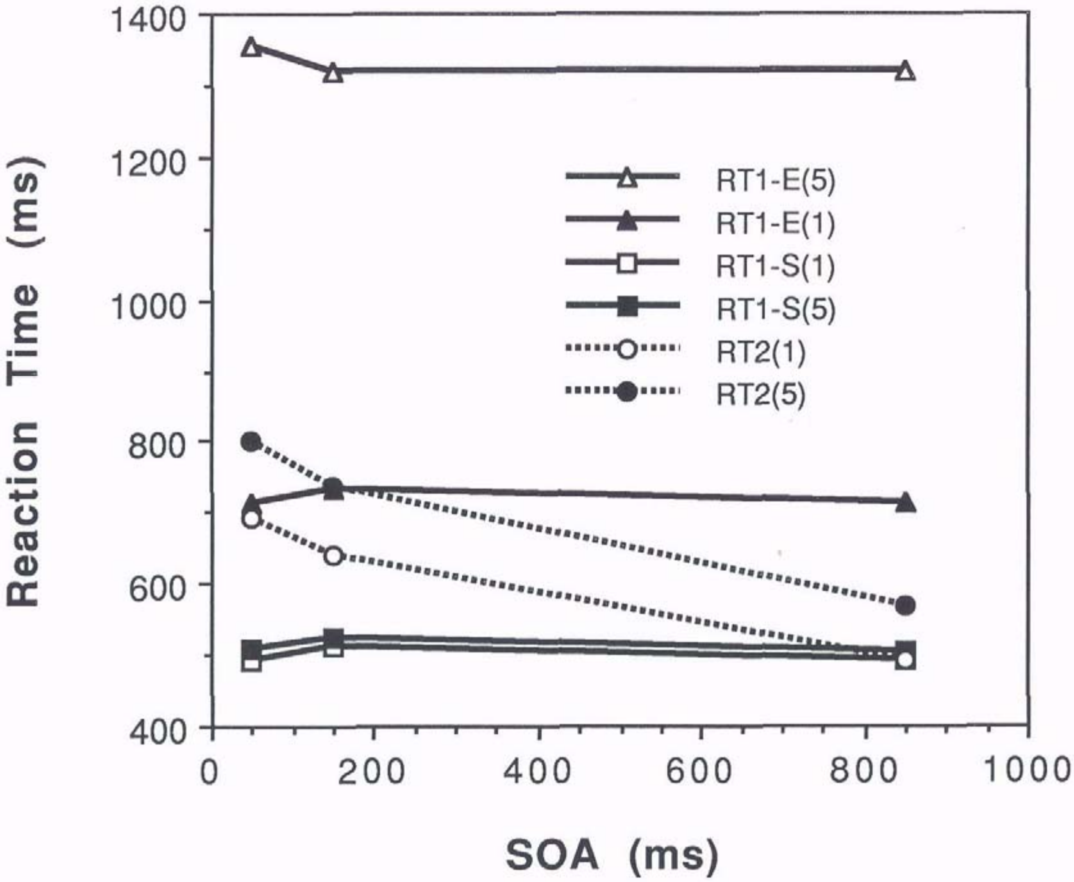


complexity 5, F(1,20)=13, p<.005, MSe=.0013; the effect of SOA was nonsignificant, F<1.

The results can be simply summarized. There is a clearcut PRP effect -- slowing of RT2 as SOA is reduced. The effect of R1 complexity on R1-end-time is large: at the shortest SOA, it takes an average of 598 ms longer to finish saying "one two three four five" than it does to finish saying "one." Increasing R1 complexity slows RT2 as well, but the magnitude of the effect at the shortest SOA is only 110 ms. Roughly speaking, then, the mean effect of R1 complexity on RT2 was 18 percent as large as its effect on R1-end-time. One puzzling feature of the data is the additive effects of SOA and complexity on RT2; if complexity affects the duration of a substage which delays task 2, then plainly RT2 should be slowed more when the SOA is shorter. The absence of such an interaction might be an anomaly, or it might indicate the fact that complexity is affecting RT2 by some means other than postponement.

Additional Two-Session Data

An additional group of seven subjects performed two sessions of this experiment and their second sessions were analyzed, so that we could see if one session of practice produced any marked changes in performance. The pattern of results was basically unchanged, with slightly more propagation of R1 complexity onto RT2 (235 ms at the 50 ms SOA, from a 687 ms R1 complexity effect on RT1 completion, or 34 percent propagation.)

Inter-response Dependencies

A PRP experiment yields a bivariate RT distribution that can potentially provide strong additional constraints on theory. In previous research, it has been observed that RT1 and RT2 are generally positively correlated

(Gottsdanker & Way, 1966), and also that the details of this dependency support single-channel postponement models (Pashler, 1989). To characterize the bivariate distribution, the R1 -start-times within a condition (i.e., all scores from a given SOA and R1 complexity) were rank-ordered and divided into five quintiles. The RT2s that corresponded to the R1-start-times in a given quintile were averaged. The effect of quintile was significant, F(4,80)=33.2, p<.001,MSe=7692, and it interacted with SOA, F(8,160)=4.2,p<.001,MSe=2992, reflecting more propagation at the shorter SOAs as found in earlier studies (Pashler, 1989; 1990; Fagot & Pashler, 1992). Averaged across SOA, mean R1-start-times in the quintile increased from 373 to 684 (increase = 311) from quintile 1 to 5. The corresponding increase in RT2 was from 605 to 714 (increase = 109).

The corresponding analysis was performed to determine how RT2 varied as a function of R1-duration (i.e., R1-end-time minus R1-start-time). The RT1-durations increased from 415 to 686 (an increase of 271 ms.) The corresponding increase in RT2 was from 650 to 689 (an increase of 39) between R1-duration quintiles 1 and 5.

Thus, the amount of trial-to-trial variability in the onset time and duration time for R1 was quite similar. However, while 35 percent of the trial-to-trial variability in R1-start-time propagates onto RT2 (by this measure), only 14 percent of the trial-to-trial variability in R1-duration propagates onto RT2. Informally speaking, on trials in which subjects were much slower than usual to start talking, their button push responses were somewhat slower than usual; whereas on trials in which subjects took much longer than usual to say what they had to say, the button responses were less affected. (The correlation between R1 -start-time and R1-duration was computed within each condition, and the average was slightly <u>negative.</u> r=-0.15).

Relative Timing of Responses

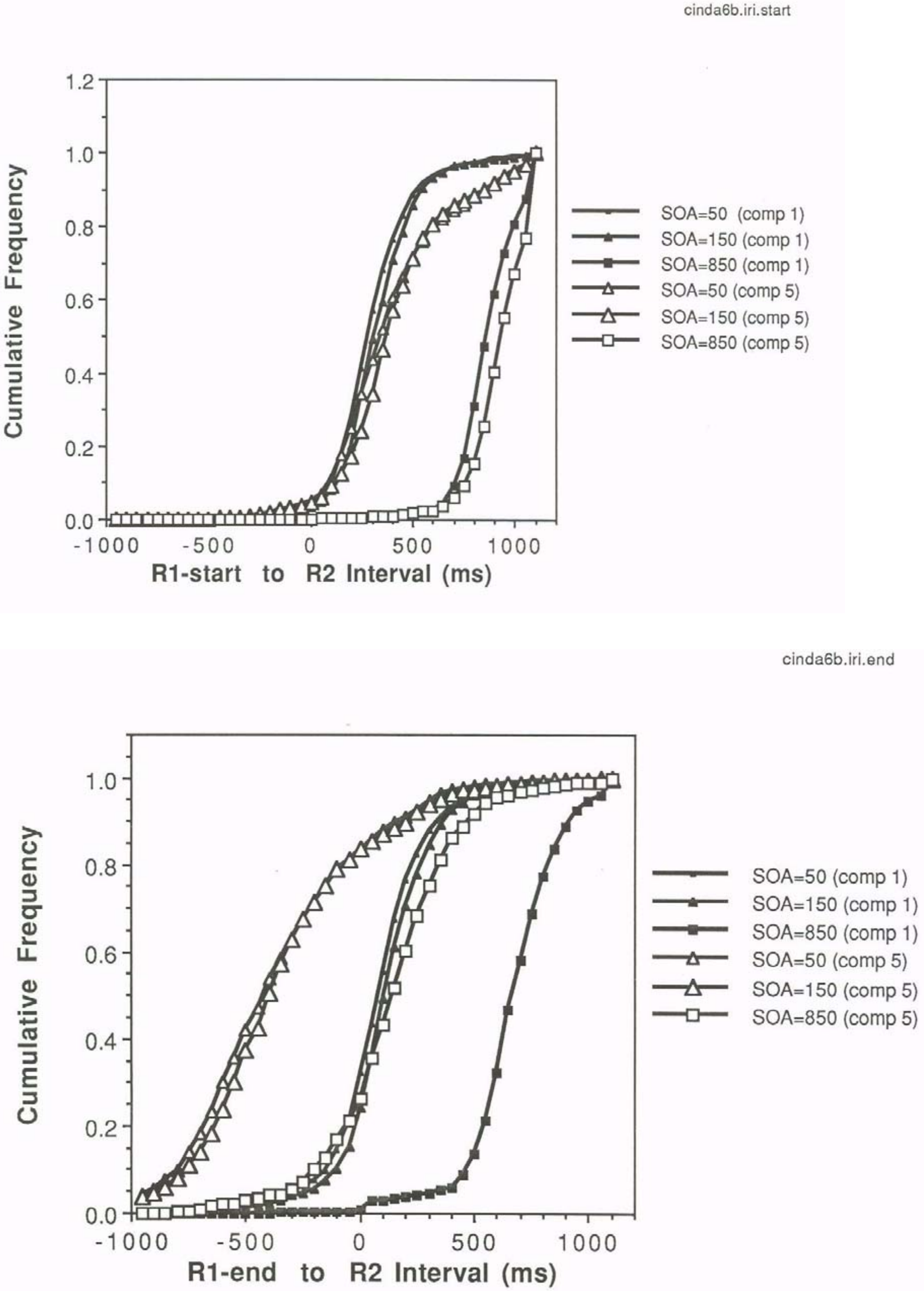
The data suggest that producing a more complex R1 does delay R2 somewhat, although not nearly so much as it delays the completion of R1 itself. This pattern of mean RTs is consistent with the possibility that on a fraction of trials, subjects delay R2 until after the entire R1 sequence is completed, while on the majority of trials, there is no sequence-related R2 slowing whatever.

The distribution of inter-response intervals should shed some light on the possibility of probabilistic postponement. RT distributions are usually "Vincentized" in order to examine the typical shape of an individual subject's RTs (i.e., the value of the xth percentile in the average distribution is obtained by taking the values corresponding to the xth percentile for each subject, and averaging these across subjects.) However, we were specifically interested in the frequency with which particular absolute inter-response intervals occurred. Therefore, the aggregate distribution may be more revealing than the Vincentized distribution for present purposes. Figure 4 (Top Panel) shows the cumulative distribution function (CDF) for the interval between the time R1 started and the time at which R2 occurred, in the aggregate data set.

*** INSERT FIGURE 4***

First, note that reversals of the preferred order of responding (i.e., R2 starting before R1 starts) do occur at the shorter SOAs, but they are quite rare. Second, note the growth of the CDFs for short-SOA trials. The CDFs grow more gradually when R1 is complex rather than simple. Given the fact that R1 starts at pretty much the same time regardless of complexity, what one is looking at is simply the slowing of R2 with R1 complexity. The fact that it takes the form of a shallower CDF indicates that having a more complex R1 produces IRIs that take a wide range of values.

4. Experiment 1 aggregate cumulative density function of inter-response intervals between R1 and R2 as a function of complexity (1 vs. 5) and SOA (50, 150 and 850 ms). Top Panel: IRI computed from <u>start</u> of R1; Bottom Panel: IRI computed from <u>end</u> of R1.



We can also see this "smear" from the vantage-point of the completion of R1. Figure 4 (Bottom Panel) shows the aggregate CDF for IRIs defined as the interval between when R1 ended and when R2 occurred. Note how widely these IRIs are distributed over the interval between -1000 and zero, for the short SOA conditions with the more complex R1. In other words. In other words, for complexity 3 trials, the vast majority of the time R2 occurs during execution of R1.

Summary and New Questions

The data reject the hypothesis that the execution of RT1 simply postpones response selection in task 2, The complexity effect slows the completion of RT1, but has a much smaller effect on RT2; similarly, spontaneous trial-to-trial variability in R1 onset delays R2, but trial-to-trial variability in R1 duration does so less. Thus, the single-channel bottleneck clearly does not simply encompass response execution in its entirety (at least for this situation.)

However, increasing the complexity of R1 does slow RT2 to some degree. We can make a few limited conclusions can be reached about the nature of this partial slowing. First, it might not reflect postponement of task 2 at all, given the absence of an interaction of SOA and complexity, as noted earlier. Second, and more important, the distribution of IRIs shows that increases in R1 complexity are associated with modest slowing on a large number of trials, rather than drastic delays on a small fraction of trials. This issue will be explored further below.

Experiment 2

In the previous experiment, the response complexity manipulation involved varying the length of a sequence that subjects have had a great deal of practice producing outside the laboratory. One might wonder, then, whether the major conclusion of the first experiment - that second-task response selection is only fractionally delayed by production of this sequence, and is not postponed by it -- might apply only to heavily practiced sequences of this sort. To examine this question, Experiment 2 required subjects to produce a short or long sequence that was arbitrary and not already familiar to the subjects.

In task 1, subjects responded to the letter "A" or "B" by saying out loud either "one" or "two three two", respectively. The second task was a tone identification task with manual response, just as in Experiment 1. The change in task 1 offered an advantage over the method of Experiment 1: the sequence starts with a different element and therefore subjects could not initiate production of the sequence before completing response selection (without making many errors). It has the drawback that different initial sounds might be picked up by the equipment at slightly different times, producing spurious differences in observed production time. (It is not possible to get around this with ordinary counterbalancing, since using different digit sequences would be likely to alter the S-R compatibility, possibly to a large extent.) Given that our primary interest here is on the rather gross effects of sequence length on the time to complete the R1 sequence, this drawback seemed relatively unimportant.

Method

Subjects

Twenty-one undergraduate students at the University of California, San Diego participated in the experiment in partial fulfillment of a lower division course requirement; usable data was obtained from fifteen (see below).

Apparatus and Stimuli

The apparatus and stimuli were identical to that of Experiment 1.

Design and Procedure

The design and procedure were identical to that of Experiment 1 with the exception of the mapping from the first stimulus to the first response. In this experiment, subjects said either "one" or "two three two" in response to the letter A or B, respectively.

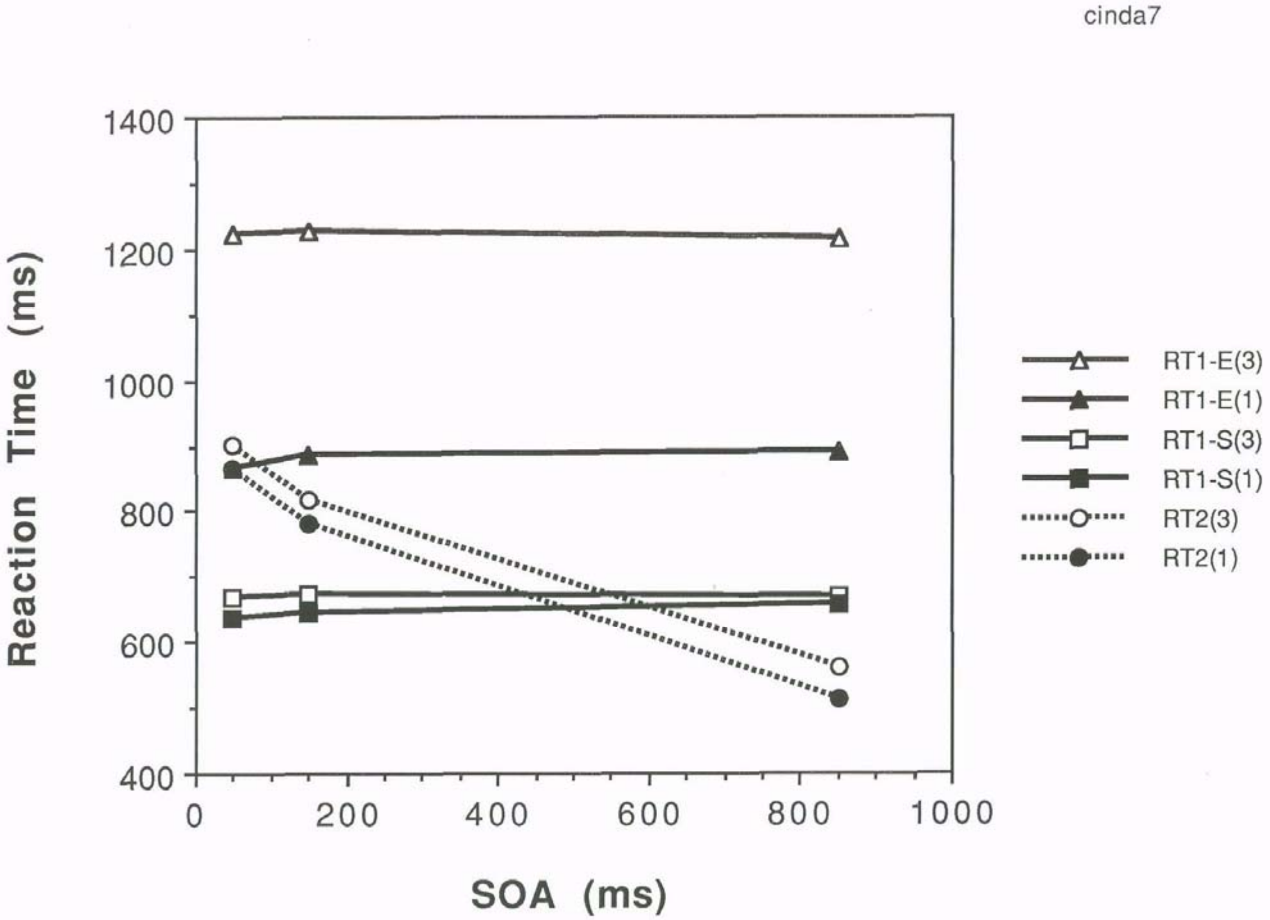
Results and Discussion

Two subjects were discarded because they had overall R1 error rates of approximately 40% and 25%, which were markedly deviant (without them, the mean was 4.9% [sd=4.8%]). Another four subjects did not follow the instructions regarding maintaining rapid responding to the first stimuli and avoiding response-grouping; their RT1s increased by an amount between 300 and 600 ms as the SOA was lengthened, indicative of grouping (Pashler & Johnston, 1989); each had R1-start-times in the long SOA condition that were in excess of 1450 ms (without them, the mean was 664 ms [sd=174 ms]). Their data were not included (although the overall pattern of results discussed below would not be greatly altered if they were included.)

Figure 5 shows the mean RTs to start and complete the first (vocal) response, and the manual RT2, all as a function of SOA and first response complexity (saying "one" vs. "two three two"). Cutoffs were as in Experiment 1.

*** INSERT FIGURE 5***

The time to begin the vocal R1 was not significantly affected by complexity: for saying "one", R1 -start-time(1) was 646 ms, and for saying "two three two" R1-start-time(3) was 672 ms, F(1,14)=3.1, p>.09, MSe=4918. The effect of SOA was also not significant, F<1, and the interaction of SOA and complexity was also nonsignificant, F(2,28)=1.6, p>.20, MSe=531. As noted



5. Mean RTs for Experiment 2 as a function of SOA. RT1-S and RT1-E are latencies to start and end first-task response; RT2 is latency for second-task response. (1) and (3) refer to the complexity of the first task (one vs. three element response sequences, respectively.)

earlier, the voice key might not have picked up these different sounds at precisely the same time, so not much can be made of this particular comparison.

The time to complete the vocal R1 was, obviously, much affected by R1 complexity: R1-end-time(1) was 879 ms, while R1-end-time(3) was 1223 ms, F(1,14)=59, p<.001, MSe=45273. The effect of SOA on R1-end-time was not significant, F<1, nor was the interaction of R1 complexity by SOA, F<1.

The RT for the manual second-task response was 883, 800 and 537 ms for SOAs of 50, 150 and 850 ms, respectively. This PRP effect was significant, F(2,28)=248, p<.001, MSe=3962. The second response was slower overall when R1 was saying "two three two" (RT2(3) = 760 ms) than when R1 was saying "one" (RT2(1) = 720 ms), F(1,14)=12.1, p<.005, MSe=3003. The interaction of R1 complexity and SOA was again nonsignificant, F<1. R2 error rates were .054 for R1 complexity 1, and .044 for R1 complexity 3, but no error rate effects were significant.

The results again show a clearcut PRP effect - slowing of RT2 as SOA is reduced. At the shortest SOA, it takes an average of 344 ms longer to finish saying "two three two" than it does to finish saying "one." This R1 complexity effect on R1-end-time shows up significantly in RT2 as well, but the magnitude of the effect is only 40 ms. Roughly speaking, then, 12 percent of the R1 complexity effect on R1-end-time shows up on RT2.

Inter-response Dependencies

The relationship between RT2 and RT1 across trials was analyzed as in Experiment 1. The effect of quintile was significant, F(4,56)=107.0, p<.001, MSe=15406, and it interacted with SOA, F(8,112)=6.8, p<.001, MSe=7999. Overall, mean R1-start-times in the quintile increased from 442 to 975 (increase

= 533) from quintile 1 to 5. The corresponding increase in RT2 was from 610 to 952 (increase=342).

The corresponding analysis was performed to determine how RT2 varied as a function of R1-duration (i.e., R1-end-time minus R1-start-time). The RT1 durations increased from 283 to 529 (an increase of 246 ms); meanwhile, the RT2s increased from 731 to 813 (an increase of 82) between quintile 1 and 5 of R1-duration.

Thus, using this measure and averaging across SOAs, 64 percent of the trial-to-trial variability in R1-start-time propagated onto RT2, while 33 percent of the trial-to-trial variability in R1-duration propagated onto RT2. (As in the earlier experiment, there was a slight negative correlation between R1-start-time and R1-duration, r = -0.11).

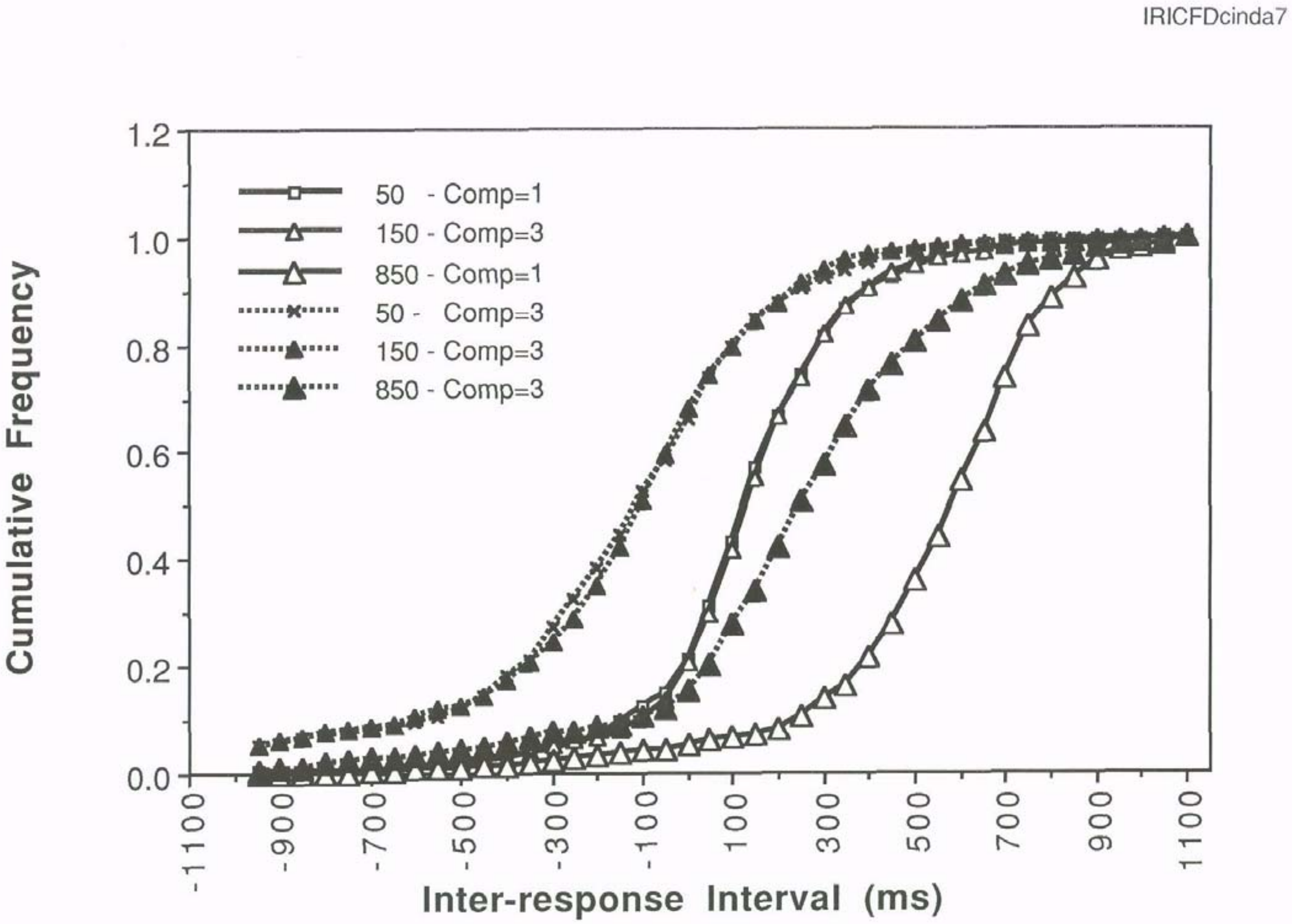
Inter-response Intervals

The inter-response intervals between R1 -end-time and RT2 were computed as in the previous experiment and they are presented in Figure 6, The results are very similar to those of Experiment 1, rejecting the hypothesis that R1 execution completely delays the second task on some proportion of the trials, and leaves it unaffected on the remainder.

*** INSERT FIGURE 6***

Conclusions

The results parallel those of Experiment 1 very closely, thus indicating that the production of a vocal response sequence is not a critical stage for arbitrary sequences of words. Again, however, increasing the complexity of R1 produces a nonzero delay in RT2. As in Experiment 2, the effects of complexity



6. Experiment 2 aggregate cumulative density function of inter-response intervals between R1-end-time and R2 as a function of complexity (1 vs. 5) and SOA (50, 150 and 850 ms).

and SOA on RT2 did not interact, although given the size of the effect itself it would probably be unwise to make too much of this.

Experiment 3A

The previous two experiments indicate that a second (auditory-manual) task does not generally wait for production of a vocal response sequence (although it is delayed to a modest extent when the duration of R1 increases.) Is this a peculiarity of vocal response production? Or of vocal responses preceding manual responses? Experiment 3 examines the effects of R1 complexity in manual as well as vocal task 1 response sequences, using a foot response in task 2. This should allow us to assess the generality of the conclusions of the previous experiment. In addition, it will provide information about the generality of the PRP effect itself, using some novel combinations of response modalities (thereby further testing the suggestions of Allport[1979], McLeod[1977a] who suggested that use of dissimilar response modalities may get around central interference.)

Task 1 required a manual response sequence in some blocks, and a vocal response sequence in other blocks; the vocal and manual tasks were matched in their cognitive demands and S-R compatibility as closely as possible. S1 was always the letter A or B. In vocal task-1 blocks, subjects responded to A or B by saying "one" or "two three two", respectively, just as in Experiment 2. In manual task-1 blocks, subjects responded to A or B by pressing a button with their right index finger, or by pressing a sequence of three keys, using their middle finger, their fourth finger, and their middle finger again, respectively. Thus, if one thinks of the keys as being numbered 1, 2 and 3, then the manual task was isomorphic to the vocal task. The second task again involved a two choice response to a tone, but in this experiment R2 was made with the left or right foot. An additional change was the inclusion of four different SOAs (50, 150, 500 and 1500ms).

Method

Subjects

Nineteen undergraduate students at the University of California, San Diego participated in the experiment in partial fulfillment of a lower division course requirement.

Apparatus and Stimuli

The apparatus and stimuli were identical to that of Experiment 2, with the addition of a foot pad, which was used for responses to the second stimulus. The foot pad consisted of two metal switches 13 cm apart. The subject rested one foot on each switch, which had to be depressed about .5 cm to be detected.

Design

The experiment was divided into 10 blocks of 48 trials each. There were three factors: SOA (50, 150, 500, and 1500 ms), type of response to S1 (manual or vocal), and complexity of response to S1 (one tap or word in the simple condition, or, a series of three taps or words in the complex condition). There were a total of 16 possible unique trial types (SOA X complexity X response type). The experiment was blocked by response type, leaving 8 possible trial types per block, each occuring 6 times within that block. The vocal and manual first-task blocks alternated; half the subjects started with a vocal block, and half started with a manual block. The order of trials was randomized within each block.

Procedure

The procedure was identical to the proceeding experiments, with a few exceptions. First, the response to the first stimulus (R1) could be either manual or vocal, depending on the block. Second, task 2 always required a foot response. When S2 was a high tone, the subjects responded by depressing the right foot pedal, and when S2 was a low tone, the subjects responded by pressing the left foot pedal.

Results and Discussion

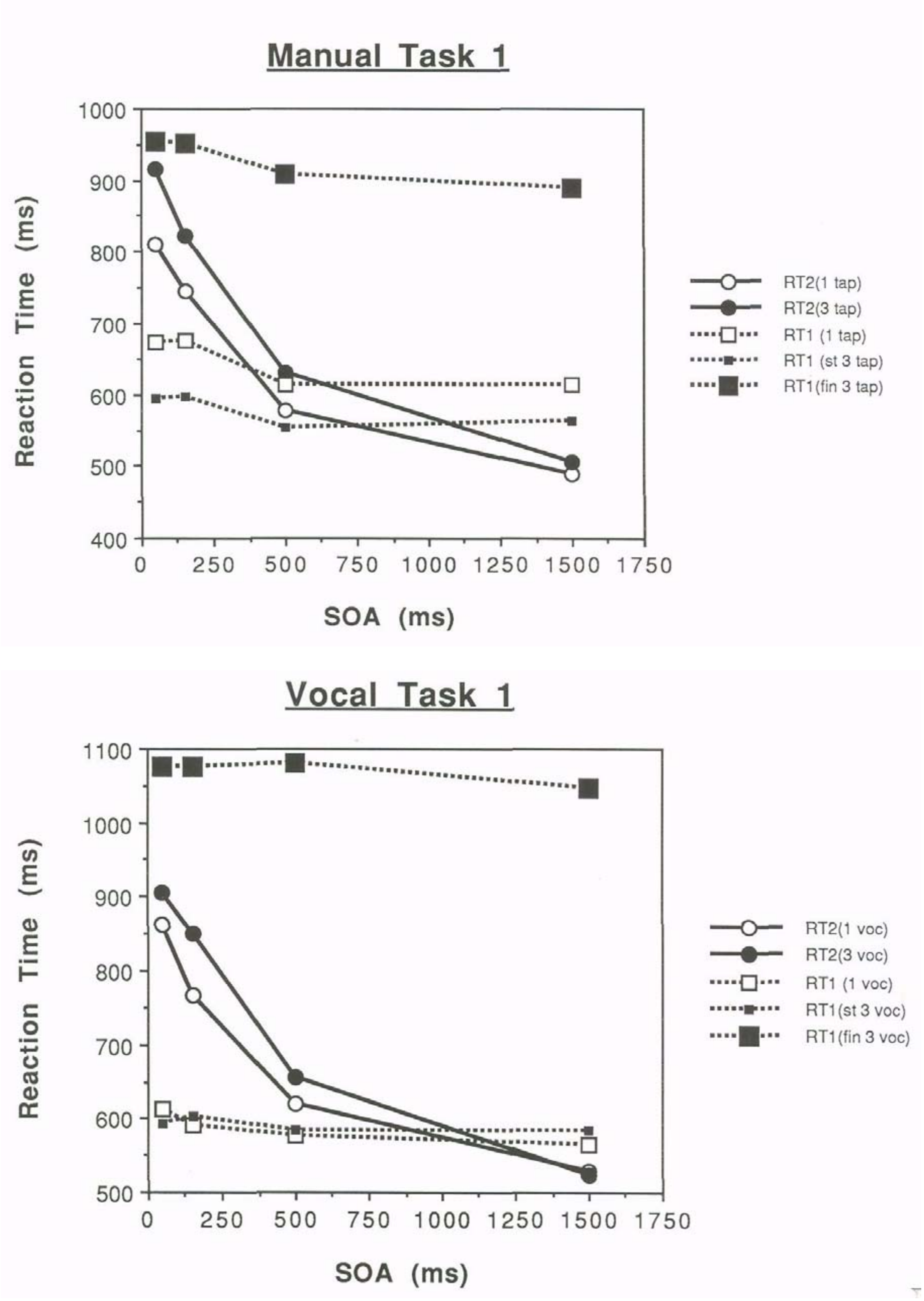
The data from one subject was discarded because of extremely slow responding. Figure 7 (top panel) shows the mean RTs to start and complete the first (manual) response, and the foot RT2, as a function of SOA and first response complexity (one vs. three keypresses). The bottom panel shows corresponding data for trials with the vocal first response.

*** INSERT FIGURE 7***

The R1-start-time was significantly affected by complexity, F(1,17)=7.1, p<.02, MSe=4195. The more complex R1 began 55 ms later for the manual task, but actually began 14 ms <u>earlier</u> for the vocal task, and the interaction of complexity with response modality was significant, F(1,17)=26, p<.001, MSe=3297. Naturally, the difference in the vocal task might simply reflect the differences in pronunciation pickup noted earlier. R1-start-time was also affected by SOA in this experiment, F(3,51)=9.1, p<.001, MSe=4622.

The R1 -end-time for R1 s composed of three elements was greater for vocal R1 responses (1071 ms) than for manual R1 responses (926), and it was also affected by SOA, F(3,51)=5.2, p<.005, MSe=3204.

The mean RT2 was 874, 796, 622 and 512 ms for SOAs of 50, 150 and 500 and 1500 ms, respectively. This PRP effect was significant, F(3,51)=171, p<.001, MSe=11365. RT2 was affected by R1 complexity, F(1,17)=31, p<.001,



7. Mean RTs for Experiment 3A as a function of SOA. RT1-S and RT1-E are latencies to start and end first-task response; RT2 is latency for second-task response. (1) and (3) refer to the complexity of the first task (one vs. three element response sequences, respectively.) Top Panel: R1 is manual response; Bottom Panel: R1 is vocal response.

MSe=6269. The interaction of R1 complexity and SOA was significant in this experiment, F(3,51)=9.3, p<.001, MSe=2213. The effect of first response modality (vocal vs. manual) was not significant, nor were any interactions involving this factor.

The error rates on R2 were .054, .044, .033 and .020 for SOAs of 50, 150, 500 and 1500, which was a significant effect, F(3,51)=8.3, p<.001, MSe=.0013. They did not differ significantly depending on whether the first response was manual or vocal, but there was an interaction between first response modality and SOA, F(3,51)=3.0, p<.05, MSe=.0011, reflecting a somewhat greater increase in error rates with SOA for R2s following manual responses rather than vocal responses. The manual error rates were .023 and .034 for low and high complexity, respectively; the difference was not significant, nor was the SOA effect (F<1).

The results show the usual PRP effect -- slowing of RT2 as SOA is reduced - whether the first response is manual or vocal. At the shortest SOA, it takes an average of 562 ms longer to finish saying "two three two" than it does to finish saying "one." This R1 complexity effect for manual responses averages 489 ms. At the shortest SOA, the slowing of RT2 due to R1 complexity amounts to 106 ms and 42 ms following manual and vocal responses, respectively. Roughly speaking, then, the percent of the R1 complexity effect on RT1 that shows up on RT2 is 22% and 7% for manual and vocal R1s, respectively.

Inter-response Dependencies

The relationship between RT2 and RT1 across trials was analyzed as in Experiment 1, looking at the mean RT2 as a function of R1 -start-time quintile, with SOA and R1 complexity as parameters. Figure 8 shows the mean RT2 as a function of R1 -duration and R1 -start-time as a function of SOA (averaged over response modality; complexity 3 only). Averaged across first response type, the effect of quintile went from 63 ms at the 1500 ms SOA to 304 at the 50 ms SOA; this interaction of SOA and quintile was significant, F(12,204)=14, p<.001, MSe=10272. Overall, the difference between the mean R1-start-times in the first and fifth quintile was 432 and 384 ms for manual and vocal R1s, respectively. The corresponding increase in RT2 was 195 ms and 216 ms, for manual and vocal R1s, respectively.

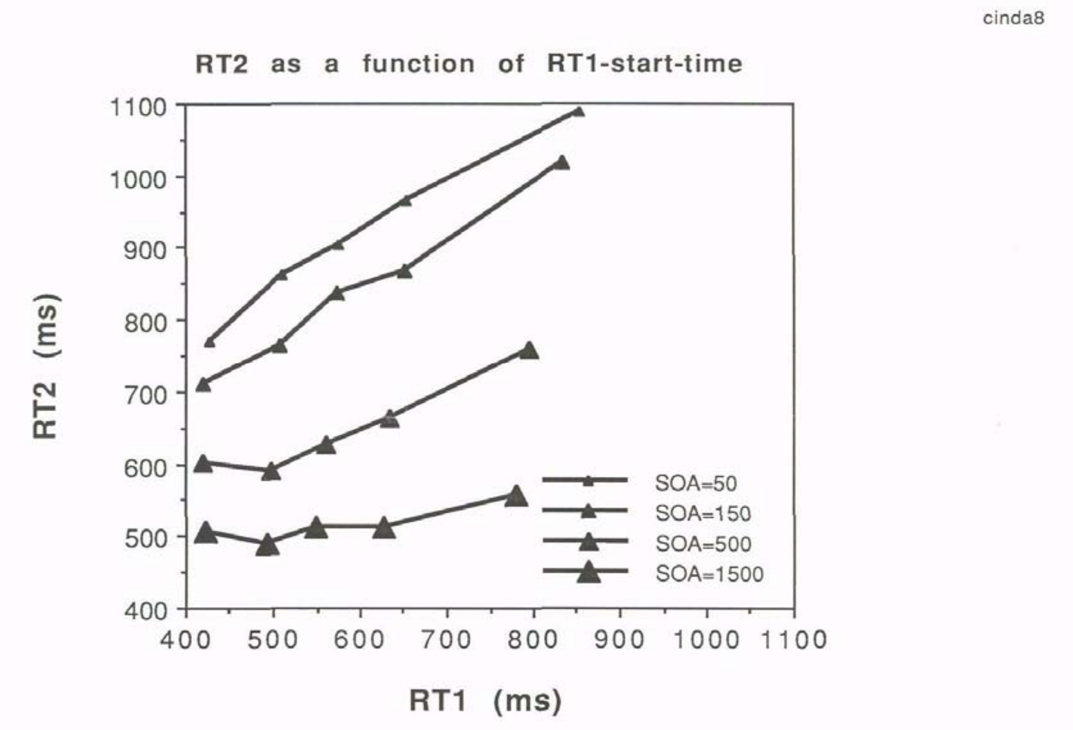
INSERT FIGURE 8

The corresponding analysis was performed to determine how RT2 varied as a function of R1-<u>duration</u>. The RT1 durations for manual and vocal responses (complexity 3 trials only) increased by 180 ms and 227 ms, respectively. The corresponding increase in RT2s was 99 and 50 ms, respectively.

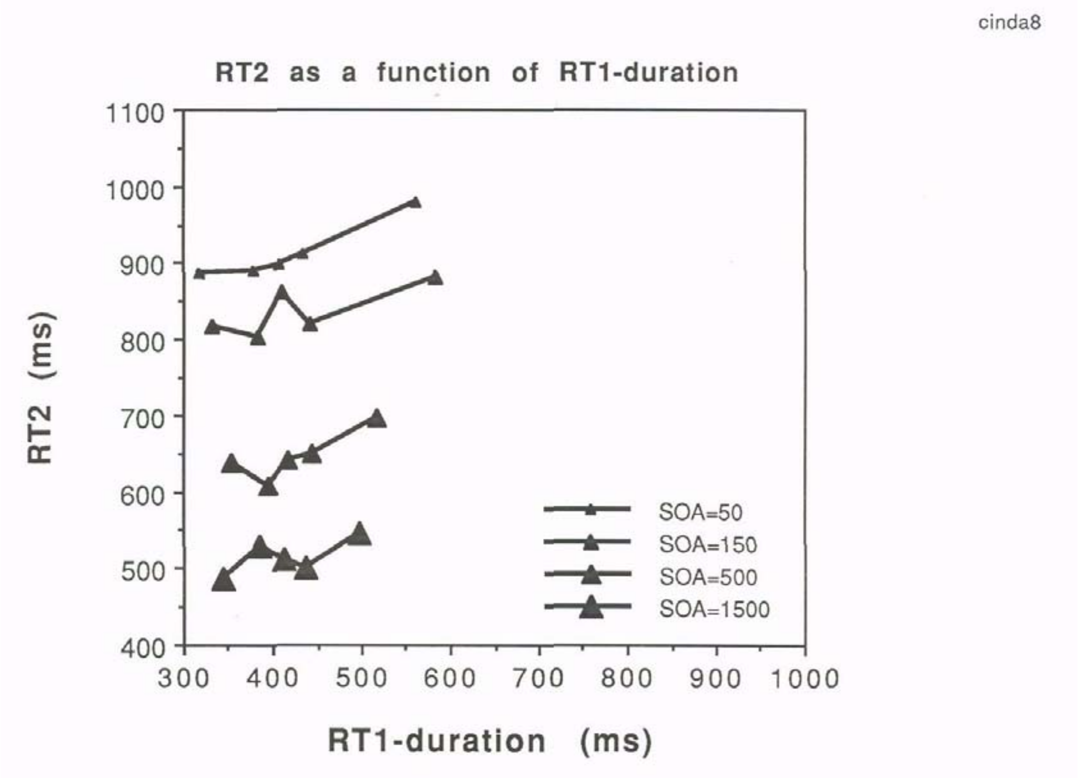
Thus, using this measure and averaging across SOAs, the percent of the trial-to-trial variability in R1 -start-time propagated onto RT2 was 45% and 56% for manual and vocal responses, respectively. On the other hand, 55% and 22% of the trial-to-trial variability in R1-<u>duration</u> propagated onto RT2 for manual and vocal responses, respectively. For the manual complexity-3 responses, R1-start-time and R1-duration was essentially uncorrelated (r=-0.024), with a slight negative correlation for vocal responses (r=-0.144).

<u>Inter-response Intervals</u>

The inter-response intervals between R1-end-time and RT2 were computed as in the previous experiment. The results for the vocal/foot response combination paralleled those of the previous (vocal/manual) experiments. However, the manual/foot combination showed substantially more slowing. It is possible to examine the relationship between R2 and any of the three R1 elements separately. For this purpose, the aggregate distribution of IRIs was



8. Experiment 3A: RT2 as a function of RT1-start-time (Top Panel) and duration (Bottom Panel), for SOAs of 50, 150, 500 and 1500 ms. Computed by quintile (see text).



computed separately from keypress 1, keypress 2 and keypress 3 to RT2. In order to help spot any tendency for the foot response to be synchronized with the any of the keypress responses, the density functions (rather than CDF) are shown in Figure 9. The mode in the density function corresponds to foot responses occurring approximately 100 ms after the last keypress response. In the typical response, then, the two response streams did not overlap. On the other hand, the results also show that overlap occurred on a small number of trials, and reversals of the two response orders on still other trials (also few in number).

*** INSERT FIGURE 9***

Comments

The results with the vocal first task extend the most salient conclusions of the first two experiments to a new kind of response. The second response (a foot response) was always delayed by the proximity to the first task - a classic PRP effect. This observation adds to the already considerable support for a central bottleneck in choice tasks which occurs irrespective of response modality (be it hand, foot or mouth). For vocal R1, the length of the response sequence required in the first task made only a very modest difference for RT2. This echoes the findings of the first two experiments. On the other hand, for manual R1, RT2 usually occurred after R1 was finished, and not surprisingly therefore, there was more propagation of random variation in R1 duration onto RT2. In this experiment, unlike the preceding two, the small effects of complexity on RT2 did interact with SOA: bigger effects at short SOAs. Given the fact that such an interaction is clearly predicted by any postponement process, this suggests that the lack of such an interaction in the preceding experiments may have been an anomaly.

Experiment 3B

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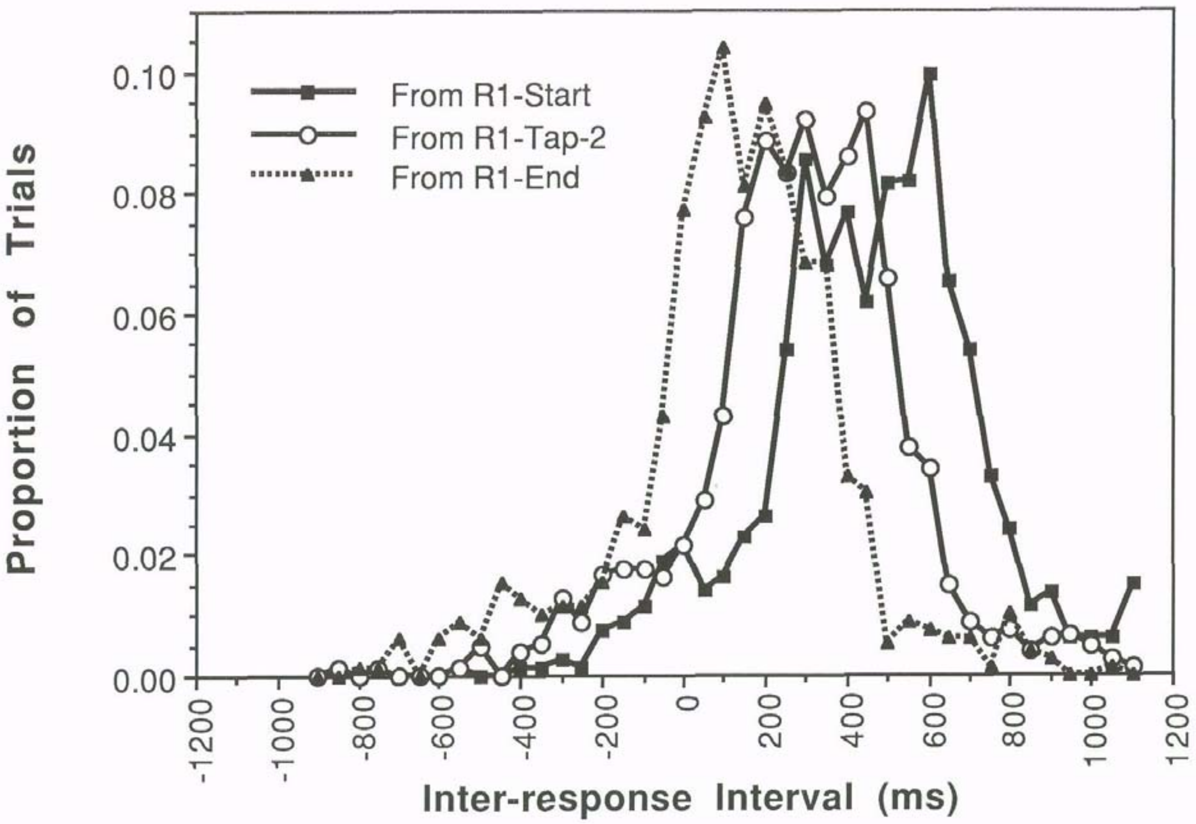


9. Distribution of inter-response intervals in Experiment 3A, computed from first R1 keypress (R1-start), second R1 keypress (R1-Tap-2) or third R1 keypress (R1-end).

To further extend the generality of the preceding results, the preceding experiment was re-run with either a vocal or a manual response required in task 1 and a manual (rather than foot response) in task 2.

Method

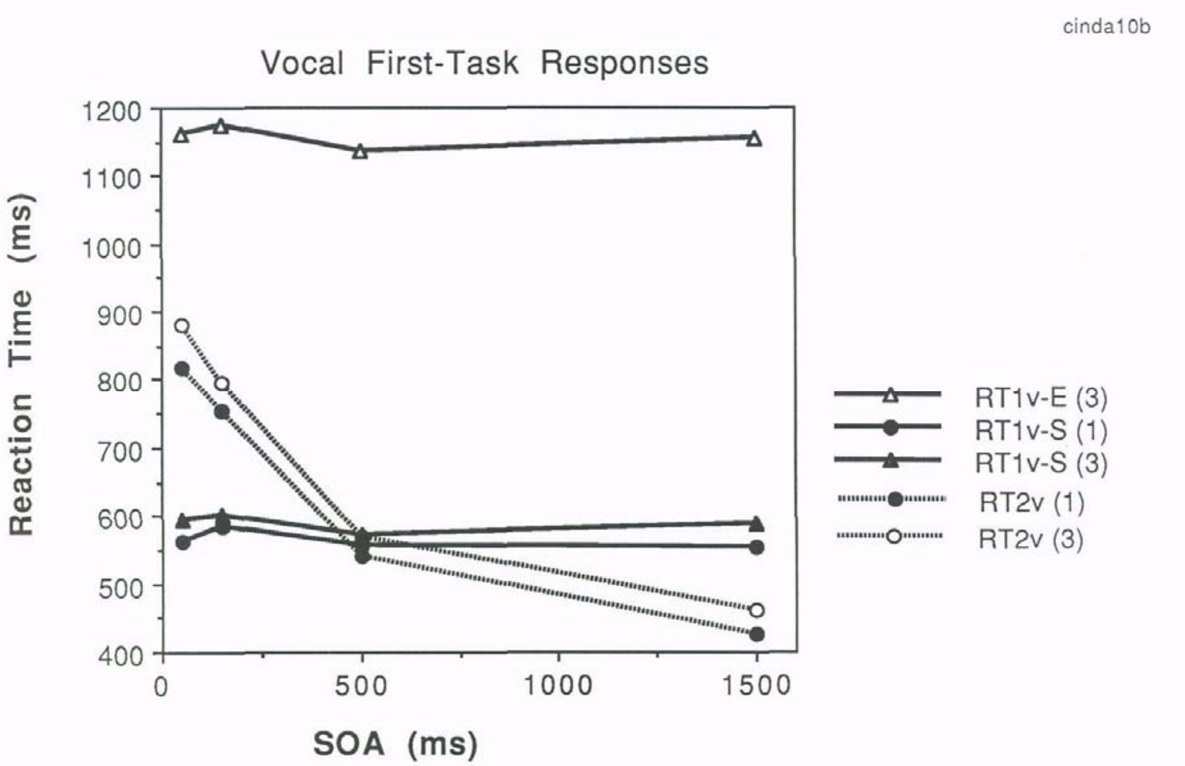
Twelve undergraduate students at the University of California, San Diego participated in the experiment in partial fulfillment of a lower division course requirement. The apparatus, stimuli and design were identical to that of Experiment 3A, with one exception: the second task required a left-hand keypress response rather than a footpress. Subjects pressed the Z key for a low tone and the X key for a high tone, using their middle and index fingers, respectively. As in the earlier experiment, vocal and keypress responding in task 1 was blocked. The procedure was identical to Experiment 3A, except that all the vocal responses were recorded and later scored for accuracy.

Results and Discussion

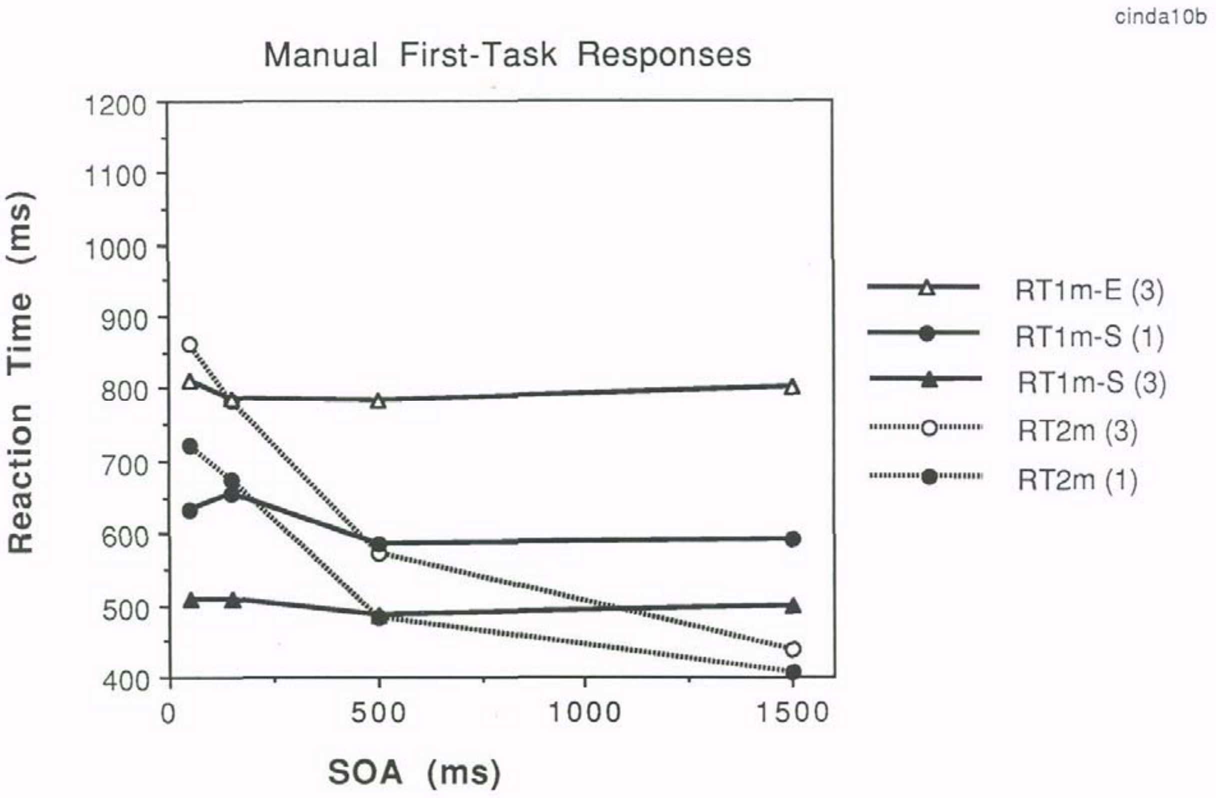
Figure 10 (top panel) shows the mean RTs to start and complete the first (vocal) response, and the manual RT2 for trials on which both responses were correct, as a function of SOA and first response complexity (one vs. three keypresses). Reassuringly, the results look extremely similar to the same condition in Experiment 3A. The bottom panel shows corresponding data for trials where the first response is manual.

*** INSERT FIGURE 10***

R1 -start-time showed an interaction of modality by complexity, F(1,11)=22.0, p<.001, MSe=10674. Just as in Experiment 3A, the sequence of three began later for the vocal response, but somewhat earlier for the manual response. The effect of SOA on R1-start-time was modest but significant, F(3,33)=6.0, p<.005, MSe=2263.



10. Mean RTs for Experiment 3B as a function of SOA. RT1-S and RT1-E are latencies to start and end first-task response; RT2 is latency for second-task response. (1) and (3) refer to the complexity of the first task (one vs. three element response sequences, respectively.) Top Panel: R1 is vocal response; Bottom Panel: R1 is manual response.



The R1 -end-time for the three-element condition was much greater for vocal R1 responses (1157 ms) than for manual R1 responses (795), but this was not affected by SOA. As one would expect, these results closely mirror the findings made with the same first tasks in Experiment 3A.

The most interesting results pertain to RT2. Not surprisingly, the effect of SOA was significant, F(3,33)=126.2, p<.001, MSe=12382, and the second response was slowed overall when the first task was more complex. This slowing interacted with SOA, F(3,33)=3.0, p<.05, MSe=3034. Of more interest, though, is the effect of task 1 response modality. The overall effect of complexity at the short SOA was 139 msec for the manual/manual condition, compared to 63 msec for the manual/vocal condition. The mean interresponse interval was actually <u>positive</u> for the manual/manual condition with complexity three. This means that, on average, second-task responses did not occur until after the entire first-task sequence was finished.

Errors in task 1 averaged 1.7%, with slightly more on the manual response (2.2%) than the vocal response (1.3%). The effect of SOA was significant (p<.05) but not monotonic (1.9, 2.7, 1.5 and .9% for SOAs of 50, 150, 500 and 1500 msec, respectively).

<u>Comments</u>

The manual/vocal results mirror those of Experiment 3A fairly well. As expected, producing the vocal first response sequence does not much delay the second (manual) response. On the other hand, a manual first response does delay the second (manual) response very substantially. Here, the results are similar to the manual/foot combination of Experiment 3A, although the postponement seems even more clearcut, with the average manual response in task 2 not occurring until after the completion of the entire sequence in task 1.

Experiment 4

The previous experiments demonstrate that a second task is not in general delayed by the entire process of executing a response sequence in T1, although it is delayed by earlier processing stages in task 1. Logically speaking, however, this does not rule out the possibility that the execution of the first element in the response is a bottleneck. For example, monitoring of feedback by the central channel as proposed by Welford might occur, but only for the feedback from completion of the first element of the response sequence.

Experiment 4 tests this possibility in the context of a different sort of first task. Here, Tw involves only one movement, namely a reaching movement from a home key toward a large square that appeared on a touch-sensitive CRT screen. The second task was the vocal choice response to a tone that was used in the first two experiments. Rather than varying the complexity of the first task, as in the previous experiments, Experiment 4 examines the effects of trial-to-trial variation in the RT1 (i.e., time between appearance of the target and beginning of the movement) and variation in MT1 (movement time, i.e., time between beginning and end of the movement.) If the second task essentially waits for selection but not the execution of the movement -- as indicated by the first three experiments - then trial-to-trial variation in RT1 should be associated with variation in RT2 while variation in MT1 should have little association with RT2.

Method

Twelve undergraduate students at the University of California, San Diego participated in the experiment in partial fulfillment of a lower division course requirement. Subjects began the trial with their right hand depressing a metal spring switch located 9 cm in front of the middle of the NEC monitor, at the same level as the bottom of the monitor. S1 was a white rectangle 4.7 cm wide and 3.6 cm high that appeared in a randomly chosen position on the face of the monitor, which measured 21 cm wide by 16 cm high. The monitor was equipped with a Elographics E274 touch-sensitive screen. S2 was a tone which was responded to vocally. The SOA was 50, 150, 500 and 1000 ms. The experiment consisted of 12 blocks composed of 32 trials per block.

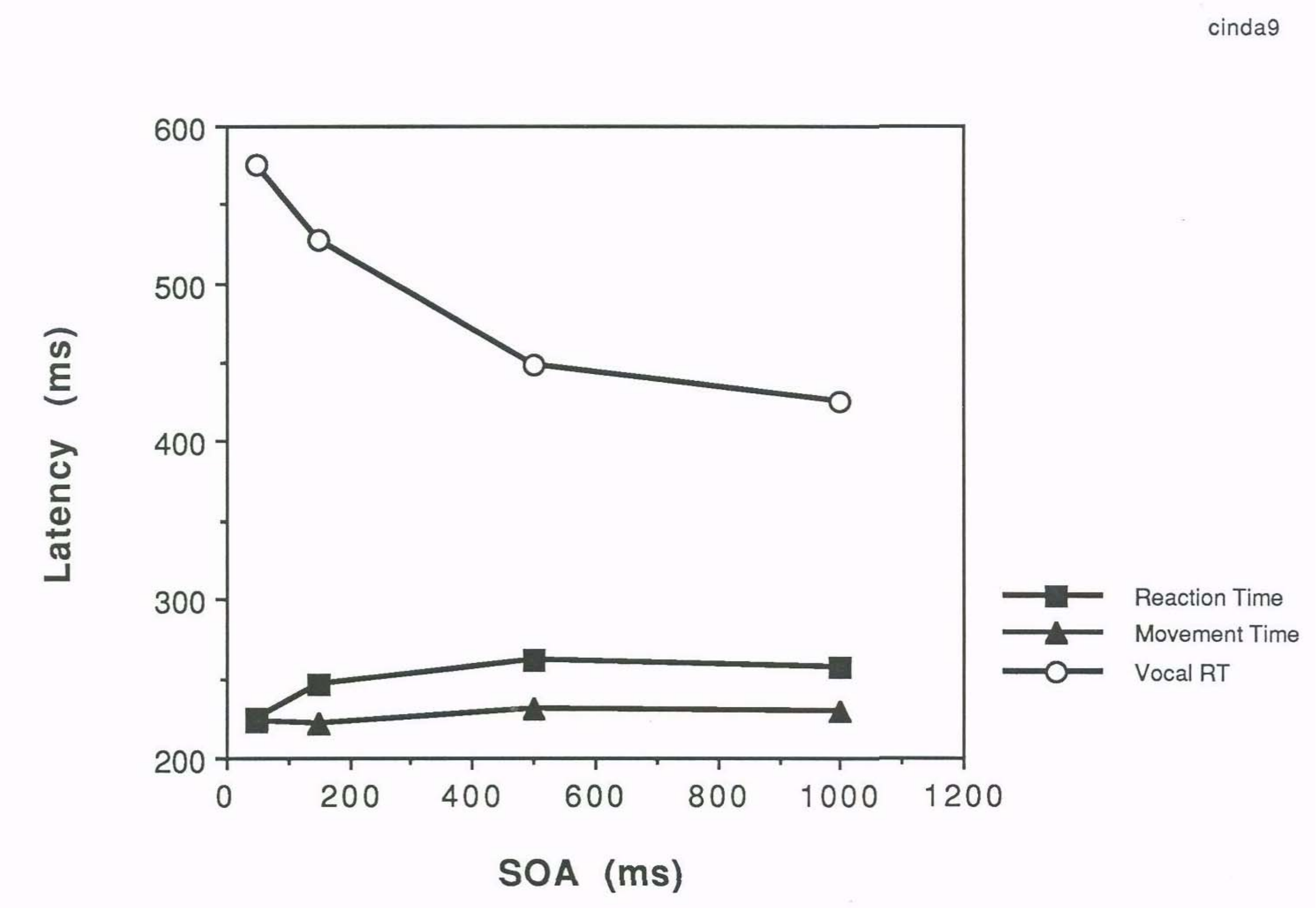
Each trial began with a message appearing on the screen that told the subject to depress the key when they were ready to begin. When the subject had pressed the key down, the screen was cleared for 1 sec. The fixation point then appeared for another one sec, at which point S1 was presented. The screen was cleared as soon as the manual response (R1) was detected. The interval between the detection of the second response and the appearance of the message starting the next trial was 500 ms.

Results

Figure 11 shows the mean reaction time and movement time on task 1, and the vocal RT2, as a function of SOA (with lower and upper cutoffs of 150 and 2000 ms, respectively). RT1 was somewhat faster at short SOAs, F(3,33)=29, p<.001. Movement time was also very slightly faster at the short SOAs (218 and 212 ms) than at the two longer SOAs (222 and 221 ms); despite the small size of these differences, the effect of SOA was significant, F(3,33)=4.1, p<.05. The vocal RT2 was 130 ms slower at the shortest SOA than at the longest, F(3,33)=18, p<.001.

*** INSERT FIGURE 11 ***

The top panel in Figure 11 shows the mean RT2 as a function of RT1 reaction time quintile, while the bottom panel shows mean RT2 as a function of RT1 movement time quintile (for these analyses, trials in which RT2 exceeded 2000 ms, or R1 reaction time or movement time exceeded 700 ms, were discarded.) The quintile effect on R1 reaction time and movement time was 140



11. Experiment 4: Mean Reaction Time and Movement Time in Task 1, and Vocal RT in Task 2, as a function of SOA.

11

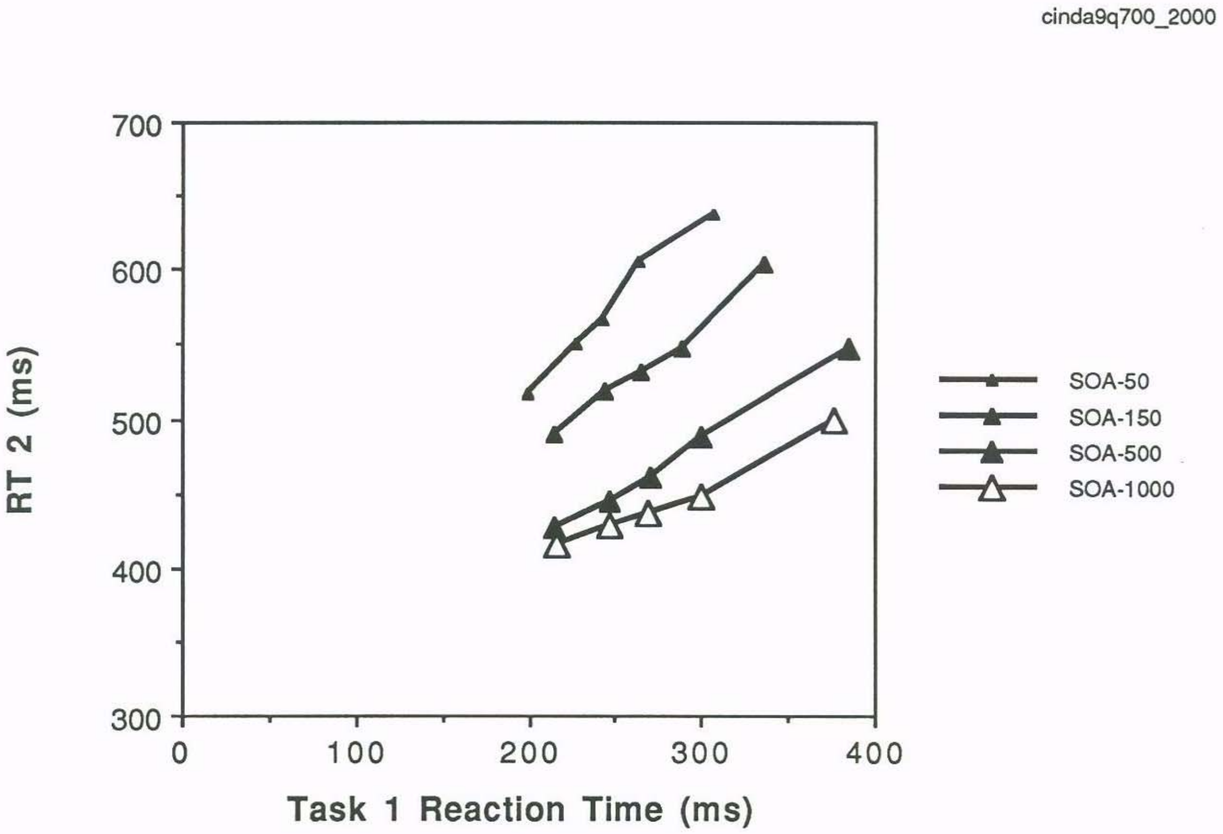
and 91, while the corresponding effects on RT2 were 109 and 46, respectively. The 46 ms R1 movement time quintile effect on RT2 is almost entirely confined to the slowest quintile. Between quintiles 1 and 4, R1 movement time slows by 59 ms, while RT2 slows by only 10 ms. By contrast, between quintiles 1 and 4, R1 reaction time is slowed by 76 ms, with a 60 ms slowing of RT2. (The R1 movement time and R1 reaction time were essentially uncorrelated, r=-.016.)

*** INSERT FIGURE 12***

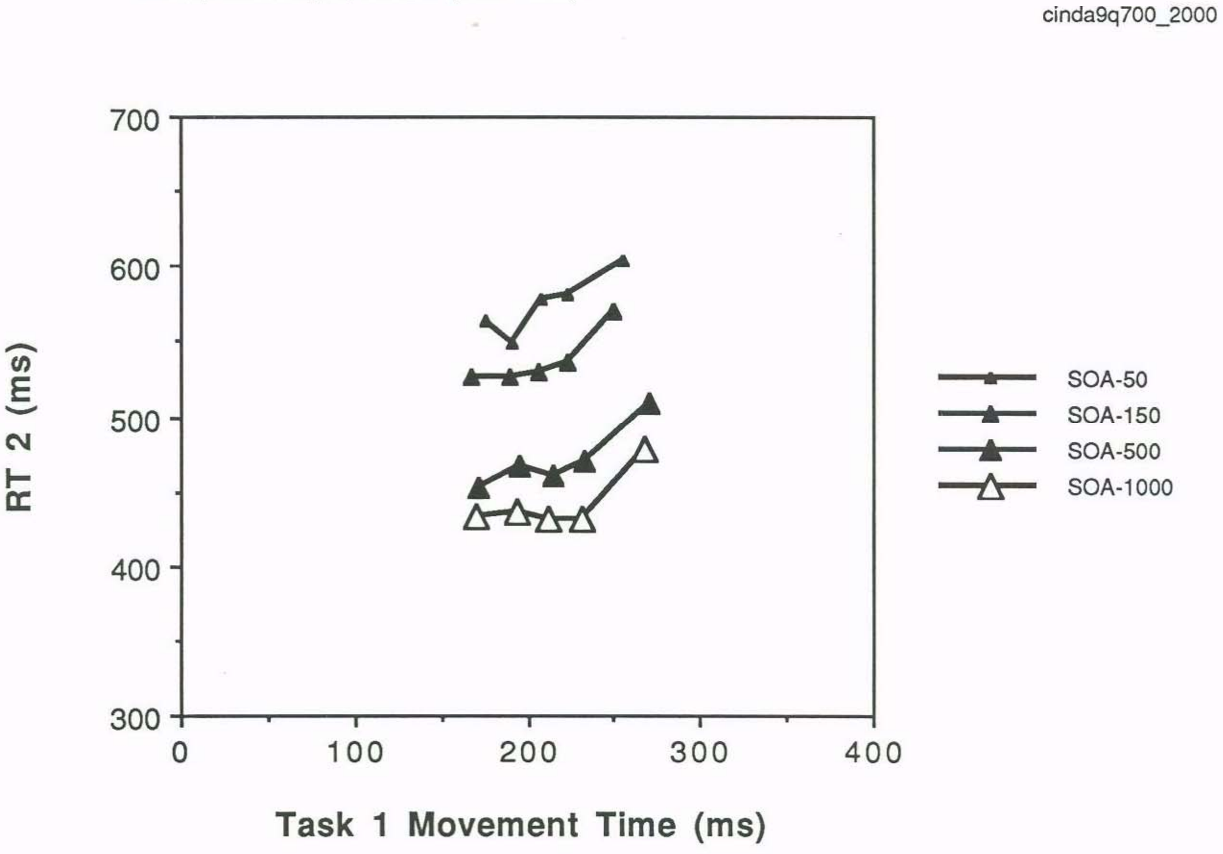
Comments

There are two primary findings from this experiment. First of all, reaching directly to a target still produces a PRP effect on a second task that follows immediately after. One might perhaps have expected otherwise, given that a few seemingly "natural" behaviors have proven to generate virtually no PRP effect: saccadic eye movements to a target (Pashler, Carrier & Hoffman, 1993) and shadowing spoken material (McLeod & Posner, 1984). The slope is not terribly steep even at short SOAs, however. This might be because the bottleneck is occupied only very briefly, or it might be because the occupation is not total; these results cannot distinguish these possibilities.

The second main finding of this experiment is that variation in time to begin the reaching movement is associated with corresponding variation in the time for the second response, while variation in the duration of the reaching movement shows much less association with RT2. This makes it very unlikely that the critical mechanism necessary for response selection in the second task must control the execution of the first response while it is happening. This fits with the findings of the first three experiments involving sequences of responses. The reason movement time has some effect on RT2 may perhaps be that on a certain fraction of trials the movement is corrected mid-stream (Meyer, Smith, Kornblum, Abrams, and Wright, 1990).



12. Experiment 4: RT2 as a function of RT1 reaction time (Top Panel) and movement time (Bottom Panel), for SOAs of 50, 150, 500 and 1500 ms. Computed by quintile (see text).



General Discussion

Carrying out the Whole Sequence is Not a Critical Stage

The primary purpose of the experiments reported here was to determine the degree to which the PRP effect reflects a bottleneck that encompasses response execution, focusing on production of sequences and, in the last experiment, on reaching movements. Previous results indicated that response selection in the second task of a PRP design is postponed by processing in the first task, apparently without regard to the modality of response (Pashler, 1990). However, as discussed in the Introduction, these results left open the question of whether second task response selection waits only for selection of the first response, or, alternatively, for execution of the first response to be completed.

The results of the present experiments show that -- when one response is vocal and the other a manual or foot response -- then task 2 does not wait for execution of a response sequence in task 1 to be completed (Figure 2A)[3]. If the central mechanism generating the bottleneck were responsible for monitoring or carrying out an R1 sequence to its completion (Figure 2C), delays in completing R1 due to increases in response complexity (Experiments 1 - 3) should have slowed RT2 and R1 completion time correspondingly at short SOAs. Furthermore, trial-to-trial variability in R1 duration in Experiments 1 - 3 should have been associated with increases in RT2 at short SOAs to the same degree as variability in R1 start time. None of these predictions were supported by the data. These contrast with the finding that increases in the duration of cognitive

[3] The results provide no particular support for the model shown in Figure 2B, but don't completely rule it out either.

stages of task 1 generally do show up fully in RT2 (Smith, 1969; Broadbent & Gregory, 1967; Pashler, 1984).

The conclusion, then, is that response execution in its entirety is not a critical stage. This also helps explain the time between S1 and R2 is often substantially less than the sum of the single-task times alone. Evidence for overlap also emerges in serial RT, where the same task is performed over and over with the subject permitted to preview stimuli ahead of time: here the rate of responding is faster with preview (Cattell, 1886), and the increases in response selection difficulty are unaffected by preview (Pashler, 1994a).

The results were quite different when both tasks require manual keypress responses (Experiment 3B) or when one task involves a manual keypress and the other requires a footpress (Experiment 3A). Under these conditions, the two streams generally do not overlap. Greater amounts of interference with manual/manual rather than manual/vocal responses have been observed before, but often this has been understood to invalidate central postponement (e.g., McLeod, 1980). The evidence described here suggests that this actually reflects an additional source of interference. There are two possible accounts of what is happening with these similar-effector tasks. First, a single bottleneck might encompass selection and execution in both tasks (as in Figure 2C). Second, there might be two separate bottlenecks (Figure 2D), one in selection, and the other in execution (of the relevant sort). The present data are probably compatible with either account, although the short interresponse intervals probably favor the second. This question should be readily testable: if there are two separate bottlenecks (Figure 2D), then when task 1 requires a lengthy manual response sequence, response selection will cease to be rate-limiting in task 2. Consequently, lengthening the response sequence in task 1 should cause factors like S-R compatibility in task 2 to have a much smaller effect when the SOA is short. Recall that this is not the case when task 1 involves only a single element response (e.g., McCann & Johnston, 1992; Fagot & Pashler, 1992). It is unusual for a psychological theory to make a detailed prediction about a three-way interaction as the dual-bottleneck model does in this case. On the other hand, if T2 response selection duration, SOA and T1 manual response complexity are all additive, then it will show that what producing one manual response sequence delays is selecting another manual response (Figure 2C). This experiment would seem well worth conducting.

Task 1 Response Execution Does Affect Task 2

Increases in the duration of R1 response execution were associated with some degree of R2 slowing even with vocal/manual and vocal/foot combinations. R2 was not slowed as much as the duration of R1, but the slowing was not negligible. The present results provide some hints about the nature of this slowing, but it remains rather mysterious. Perhaps the oddest feature of this slowing is the absence of a complexity X SOA interaction in RT2 in the first two experiments; if complexity increased the duration of a sub-stage in task 1 that delays task 2, then the degree of slowing of R2 should increase as SOA is shortened. The absence of such an interaction in these experiments may be an anomaly, given the occurrence of the expected interactions in subsequent experiments.

One possible account of R2 slowing with increases in the duration of R1 response execution would be that R1 execution does postpone task 2 completely, but only on the occasional trial. This predicts that some fraction of the time R2 will be delayed until after R1 is completed, with no R2 slowing on the bulk of trials. The inter-response interval analyses presented above do not support this account.

There are three other possibilities that seem worth considering. This first is that the second task simply proceeds more slowly when the first task response is being produced. (It might be either selection or execution of R2 that is so affected, or both.) The most familiar way of formulating this account would be to say that R1 response production "takes capacity," thus leaving less capacity left over for task 2. Given the absence of R1 slowing in Experiments 1 and 2 reported above, there is nothing much to support this idea. Still, it cannot be ruled out. A related formulation would be that there is graded, asymmetric interference: R1 execution doesn't drain capacity, but imposes a kind of cost on the other task that produces no corresponding benefit.

A second possibility is that a sub-stage of response execution in task 1 always postpones task 1. Given the modest (but significant) dependencies of RT2 on R1 duration, this sub-stage would have to encompass a portion of the variability of RT1 (or its duration would have to be correlated with response execution). But what could this sub-stage be? It could conceivably be motor programming, if this operation continues after R1 has begun (as Sternberg, et al, 1978 suggested).

Another possibility - which seems more attractive to us - is that execution of R1 generally proceeds without interference, but on certain trials (disproportionately often those that operate more slowly) difficulties emerge. These difficulties require modifications of the response program based on various forms of sensory feedback -- essentially, new response selection operations. Such corrections may interrupt selection of R2, and thereby delay R2. However, there is no reason to expect these delays to result in R2 being delayed until after the completion of R1; hence, this account is consistent with the pattern of IRIs. This proposal is also consistent with recent analyses of reaching movements (e.g., Meyer, et al, 1990), and it has the further virtue of parsimony -- it asserts that it is only the central components ("stimulus-response translation", to use Welford's term) that produce delays. At present, however, this is mere conjecture, in need of further study.

Probe RT Studies

There is another important body of research -- briefly mentioned above -- which directly attempted to analyze the "attentional demands of movement", using the so-called Probe RT method (e.g., Posner & Keele, 1969; Ells, 1973; McLeod, 1980; Girouard, Laurencelle & Proteau, 1984). These experiments combined a movement task with a concurrent speeded response to an auditory probe - rather similar to Experiment 4 above. However, a different theoretical framework was adopted in this research, according to which increases in probe RT were assumed to measure the "attentional capacity demands" imposed by the movement task. Thus, response times were used as a measure of difficulty. whereas in the present approach, they are used to infer when certain processing stages occur.

Starting with Posner & Keele (1969), probe-RT studies have simply assumed that there is something called capacity (or attention) that is shared between tasks. This assumption may be unwarranted. While performance may certainly trade off between two tasks, over a coarse time scale, one finds no support for capacity sharing when tasks are examined in a fine-grained way (Pashler, 1989, 1994b). Tradeoffs may occur even if discrete mechanisms are devoted to just one task at a time, because people can vary the relative amount of time devoted to each. The term 'capacity-sharing' may be misleading in such cases, in the same way it would be misleading to postulate that "plumbing capacity" is split evenly among two homes on a given day if what actually happened was that the plumber spent the morning at one house and the afternoon at the other. The term 'time-sharing' would seem more appropriate.

Nonetheless, the results of several probe-RT studies are of interest. The studies that provide the most detailed clues about stage organization have used two manual responses.[4] McLeod (1980) found that manual probes suffered a different pattern of interference than vocal probes. His results are consistent with the idea that with the vocal probe, response execution was not a critical stage, whereas with two manual responses, it was, as the results above seem to indicate. However, the existence of substantial primary task slowing, the absence of any information about the relationship between latencies on the two tasks, and the lack of movement difficulty manipulations make probe-RT studies relatively inconclusive.

Conclusions

The present results show that when vocal sequences are combined with manual or foot sequences or other movements, response execution is not a critical stage as the model in Fig. 3C (bottom panel) would suggest. Furthermore, the existence of two general purpose bottlenecks in response selection and in response execution in general (as in Figure 3D) can also be ruled out. The results show clearly that a vocal response stream being produced as fast as possible can "run off" while a manual or foot response is

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[5] For example, Ells (1973) required a button push response to an auditory probe occurring at some point in the preparation for or execution of a manual reaching movement. He varied both number of alternatives and target size. Some of his effects can be interpreted (as in Figure 3 and 4) as suggesting that response selection is always a critical stage, while response execution is critical only for narrow targets (although this is different from Ells' analysis of his data.) Kerr (1975) found manual probe responses occurring during the execution of a primary-task stylus movement, but the probe was simple RT, making its relevance to present concerns less clear.

both selected and executed, even though the two response selections do not seem to be able to overlap (based on other studies described in the Introduction). On the other hand, the results also imply that when a manual response stream is produced, neither a foot response nor another manual response can be selected and produced (although the data don't indicate conclusively whether selection is held up or not). Most likely, this is because the production of either manual or foot responses involves a separate bottleneck of its own. This last conclusion, however, was not demonstrated conclusively by the data reported here, and will require further tests.

The results provide no support for the existence of "capacity sharing" at a fine-grained level. On the other hand, even when the response streams could operate in parallel (e.g., with manual and vocal responses), T1 response complexity still had modest effects on T2 latencies. The results provided some clues about the causes, but various possibilities remain to be distinguished empirically. To do so, future research could profitably examine additional variables such as the degree of precision required in reaching responses and whether or not visual feedback was provided. While there is obviously a great deal more to be learned about dual-task interference in programming and production of motor actions, the results described above do succeed in documenting the (widely suspected, but not demonstrated) overlap of cognitive processes and response production, and show that limitations specific to response execution arise with certain effector combinations and not others. More generally, the results suggest that analysis of the fine temporal structure of punctate-task performance in PRP experiments offers an excellent methodology for dissecting underlying causes of interference and revealing details of interference not visible with the "probe RT" methodology or with continuous dual-task methods.

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