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Making Two Responses to a Single Object: Implications for the Central Attentional Bottleneck

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Experiments with two stimuli and two responses have revealed a central attentional bottleneck and pointed to response selection as its primary locus; however, little has been said about the underlying reasons for this bottleneck. Here we explore these reasons. In the first three experiments, Ss made two separate responses to different aspects of the same object. Interference between selection of the responses persisted, ruling out the possibility that the dual-task bottleneck is caused by the input to the response-selection mechanism being limited to one object at a time. The next four experiments examined what happens when two responses are made to the same attribute of a single object. These experiments show that only one response selection occurred. Hence, the central mechanism is not limited to picking one motor action at a time. Several possible theories about the nature of the bottleneck are discussed.

Recent work has shed light on the type of interference that occurs when two simple tasks are done concurrently. In the dual-task situation, subjects are presented with one stimulus (e.g., an alphabetic character on a computer monitor) followed by a second stimulus some interval later, and subjects make a choice reaction to each stimulus (e.g., by pressing one of two keys, depending on the letter name of the stimulus). To respond appropriately to a stimulus, subjects must somehow transform the perceptual information about the stimulus into knowledge of which response to make and a motor plan for making the response. This processing can be broken into at least three stages: a perceptual processing stage, a response-selection stage, and a response-execution stage (Sternberg, 1969). Pashler and his colleagues (Pashler, 1984, 1989, 1990; Pashler & Johnston, 1989) argued that response selection constitutes a bottleneck—a stage of processing shared by both tasks that only one of the tasks can be engaged in at any time. This work supports early suggestions of Welford (1952; see also Smith, 1967).

The current evidence suggests that interference in the dual-task paradigm, when only simple perceptual processing is required, occurs exclusively at response selection. Pashler (1984) used a methodology that is sensitive to whether the effect of a manipulation occurs before or after the point in processing in which the second task is slowed because of overlap with the first task. Pashler and Johnston (1989) showed with this methodology that the interference in dual-task situations occurs after the stages affected by stimulus degradation and before or at the stages affected by stimulus and response repetition. Because stimulus degradation affects the duration of perceptual processing, and stimulus repetition affects mostly response selection (see Pashler & Baylis, 1991), the bottleneck seems to occur after perceptual analysis and before or at response selection. (Pashler, 1984, and McCann and Johnston, 1992, provide further evidence along the same lines.) There is further evidence that the bottleneck occurs after perceptual processing: Pashler (1989) showed that accuracy of the (unspeeded) report of the highest digit from a masked array of eight digits suffered little interference in an overlapping task that required a speeded response.

There is also various evidence suggesting that selection of the second response is completely postponed until the first response is selected. Welford (1952) first noted that the slope of the function that relates second-task reaction time (RT) to the stimulus onset asynchrony (SOA) in many experiments approached -1 at short SOAs, indicating that every millisecond decrease of SOA results in an equal increase of second-task RT. On this basis, he argued for a processing bottleneck. Smith (1969) found that at short SOAs, varying the number of response alternatives on the first task had almost equal effect on the RT for both tasks. This could happen only if some stage of the second task was completely postponed until some stage of the first task was completed. More recently, it has been argued (Pashler, 1989, 1990) that the strong dependence on the relative speed of the first response of second-task RT at short SOAs and the almost nonexistent dependence at long SOAs also implicate a bottleneck.

Figure 1 shows what is postulated to be the ordinary sequence of processing stages in performing two temporally overlapping tasks (with simple stimuli or stimuli in different modalities) on the basis of this research. All of the processing for the first task is unhindered by the second task. Very specific interference, however, occurs in the second task. Whereas perceptual analysis of the second stimulus is not delayed, second-task response selection is unable to proceed until the first response has been selected.

But what underlying limitations in human information-

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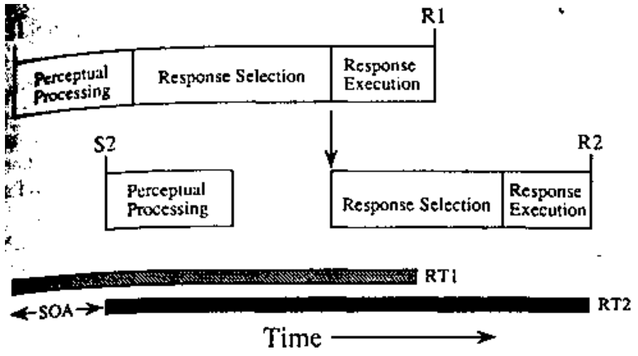

Figure 1. The processing that occurs when a subject performs two simple choice-reaction tasks. (Processing for the first task is unaffected by processing for the second. Likewise, the perceptual processing and execution of responses of the second task are not affected by concurrent first-task processing. Selection of the second response, however, cannot proceed until selection of the first is complete. S1 and S2 denote different attributes of the same object. R1 and R2 denote first-and second-task response, respectively, and RT1 and RT2 denote first-and second-task reaction time, respectively. SOA denotes stimulus onset asynchrony.)

processing machinery yields this bottleneck? The most natural assumption would be that there is a mechanism or a set of mechanisms that is fully occupied in carrying out the bottleneck processes and thus cannot work on these stages in more than one task at a time. But previous experiments do not answer many important questions about the processing performed by this mechanism or set of mechanisms. The present study is a first attempt to paint a clearer picture of the processing mechanisms responsible for the critical bottleneck stages of dual tasks. To do this, we investigate two nonstandard dual-task situations in which the subject sees one object and makes two responses. In Experiments 1-3 we examine performance when two responses are made to different attributes of the same object. In Experiments 4-7, we look at what happens when two responses are made to the same attribute of an object. In each of these two cases, some candidate models of the bottleneck mechanism predict that the need to call on the bottleneck mechanism twice—once for each task—will be eliminated. The outcome of these two sets of experiments will therefore help to clarify the nature of the bottleneck mechanism. In addition, these results might have some practical implications because even though these sorts of dual-response demands have been studied little in the laboratory, they are quite common outside the laboratory.

Responses to Different Attributes of the Same Object

One plausible hypothesis, consistent with previous evidence, is that the bottleneck occurs because stimulus information is passed to postperceptual processes one perceptual object at a time.[1] Previous dual-task studies have almost always used separate objects as stimuli for the two tasks. The following are some typical examples. Pashler and Johnston (1989) used tones (considered for present purposes to be objects) and letters for the first and second stimuli. Smith (1969) used digits presented in adjacent windows of a display device as the stimuli. Broadbent and Gregory (1967) used two sets of two neon lamps for stimuli. Results from such studies therefore leave open the possibility that what initially looks like an inability to select more than one response at a time may actually reflect an inability to initiate multiple response-selections on more than one object at a time.

This suggestion draws plausibility from findings that seem to indicate that some other attentional processes are allocated to whole objects at a time. Duncan (1984) showed that two perceptual discriminations on the same object could be made with little or no decrement in accuracy relative to when only one discrimination was made. He found, however, that when two discriminations were made on different objects, the second discrimination suffered significantly. This is most easily explained if one assumes that visual attention is allocated to one object at a time. When extraneous items are presented in a visual task, RTs and error rates generally show a cost of filtering out the extraneous items (C. W. Eriksen & Hoffman, 1972). Treisman, Kahneman, and Burkell (1983) showed that when the extraneous items and the target item can be grouped as part of the same object, this filtering cost is reduced. Response competition effects, however, which probably depend on how much processing the distractor item receives, are increased when the target and distractor are part of the same perceptual group. Driver and Baylis (1989) found that the effect of distractor items on speed of response to a target item (after B. A. Eriksen & Eriksen, 1974) was greater for items that were grouped with the target by common motion than for items grouped with the target by spatial proximity.

All of these findings broadly support a currently popular view of the role of focal visual attention. According to this view, preattentive analysis results in the segregation of the visual field into perceptual groups or objects (e.g., see Neisser, 1967; Treisman & Gelade, 1980). Focal attention is then restricted to these perceptual groups and applied to the entire group regardless of whether only part of the group is pertinent to the present task. One function of visual attention may be to integrate the perceptual features within the focus of attention into whole objects (Treisman & Gelade, 1980). The question we consider here is whether the allocation of attention by perceptual objects has any relevance to response selection.

We consider two preliminary models of how a response-selection bottleneck might occur. According to the first model, after an object has been identified, focal attention is used to send the stimulus information from that object to the response-selection stage. At this point, response-selection machinery suffices to select the response or responses that correspond to that object (whether there be one or two such responses). In contrast, the bottleneck mechanism in the second model is limited by the number of responses it can select at once, but the number of objects on which it operates is irrelevant. This latter concept of a response-selection bottleneck has simply been assumed by Welford (1952), Pashler (1984), and others. To test among these hypotheses, responses

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[1] In this article, visual stimuli that would be grouped together by Gestalt properties will be spoken of as belonging to a single object, although this may overstate the point.

and objects must be unconfounded. This is the goal of Experiments 1-3.

Experiment 1

In the present experiment, S1 and S2 denote different attributes of the same object. First, a vocal response was made to the name of a letter, and then a keypress was made to the color of the same letter. To examine how two tasks interfere with each other with any precision, it is necessary to vary the interval between the initiation of processing for each task: the SOA. To achieve this, the letter was first presented in gray, and after an SOA of 50, 150, 350, or 900 ms, the color of the letter was changed to either red or blue. If evidence for a bottleneck is found with this pair of tasks, it cannot be caused by postponement of processing on one object while another object is being processed, because there is only one object present (the possibility that the color change amounts to an object change will be dealt with later).

Method

Subjects. Twenty-two undergraduate students at the University of California, San Diego, took part in partial fulfillment of a course requirement. The data on 4 of these subjects were lost because of computer failure, and 1 subject's data were discarded because of unusually high error rates.

Apparatus and stimuli. IBM PC microcomputers with NEC Multisync monitors (with Paradise VGA color boards) were used for data collection and stimulus presentation. In addition, Gerbrandts Model G134IT voice-activated relays were connected into the game ports of the computers to detect the onset of vocal responses. The stimuli were uppercase letters chosen with equal probability from the entire alphabet. The letters appeared initially in gray and then turned either red or blue. Letters appeared on a black background with dimensions of about 2.8 cm in height and 1.7 cm in width, or 2.67° x 1.62° visual angle on the basis of a typical viewing distance of 60 cm.

Design. The experiment consisted of 1 practice and 10 experimental blocks of 40 trials. The practice block preceded the experimental blocks, and no data were recorded from it. Every block included four different SOAs (50, 150, 350, and 900 ms) that separated the onset of the letter and the onset of the final color of the letter. Each SOA occurred 10 times within a block. On half of the trials the letter turned red, and on the other half it turned blue. The order of presentation within each block was randomized.

Procedure. Subjects received written instructions describing the task. The vocal response was called the *first task,* and the manual response was called the *second task.* The instructions stressed that the subject should respond to both tasks as fast and as accurately as possible and put special emphasis on making the vocal response quickly. The sensitivity of the voice-triggered relay was adjusted so that it picked up the subject's voice but not keypresses.

Each trial was initiated with the presentation of a white plus sign for 1,000 ms in the center of the screen as a fixation point. Two hundred fifty milliseconds after the offset of the fixation point, the stimulus letter was presented, and after the SOA of 50, 150, 350, or 900 ms the color of the stimulus changed to either blue or red.

The subject made two responses. The first response was to speak (into the microphone held in the subject's left hand) the name of the letter that appeared as the stimulus in the trial. Reaction times were measured from the onset of the stimulus until the voice-triggered relay detected sound. The second response was to press the *B* or *N* key, which corresponded to a stimulus color of red or blue, respectively. Subjects used the index and middle fingers of their right hand for this response. Reaction times for the second response were measured from the onset of the stimulus color to the detection of the keypress by the computer. If an incorrect key response occurred, an 800-Hz tone sounded for 300 ms to indicate an error. The duration of the interval between the second response and the fixation point for the following trial was 1,500 ms.

After each block, the subjects were instructed to rest until they felt like proceeding. During this period the mean RTs for both the first and the second response for all preceding blocks were displayed to the subject.

Results

For each SOA, we obtained 1,700 trials (17 subjects x 100 trials at each SOA). Trials in which a vocal response was not detected or in which either response was made faster than 150 ms or slower than 1,800 ms were not included in the analysis.

Figure 2 shows mean correct RTs as a function of SOA for both responses. Between SOAs of 150 ms and 50 ms, the second-task reaction time (RT2) was increased by 50 ms. The effect of SOA on RT2 was significant, $F(3, 48) = 117$, $p < .001$, although the effect of SOA on the first-task reaction time (RT1) was not significant, $F(3, 48) = 1.1$, $p > .35$, as is apparent from Figure 2. The error rates to the second task were 7.5%, 8.0%, 7.5%, and 8.1% for SOAs of 50, 150, 350, and 900 ms, respectively, and there was no significant effect of SOA, $F(3, 48) = 1.8$, $p >$. 15. First-task responses were not recorded, so error rates on that task are unavailable.

Figure 3 shows mean RT2 as a function of SOA and the relative speed of the corresponding first-task response (RT1). We performed the following analysis separately for each SOA. First, we divided the RT1 distribution into quintiles. Next, for each quintile, we determined the mean of RT1 and RT2 of trials falling in the quintile. The points in Figure 3 correspond to the mean across subjects of the mean RT1 and RT2 scores for each quintile at each SOA.

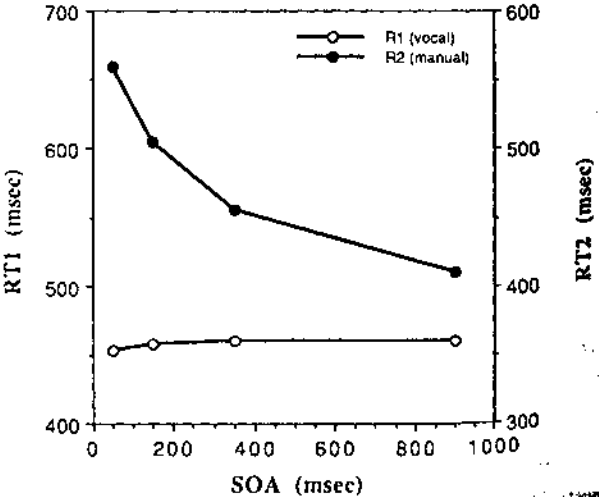

Figure 2. Experiment 1: Mean first- and second-task reaction time (RT1 and RT2) as a function of stimulus onset asynchrony (SOA). (R1 and R2 denote first- and second-task response, respectively.)

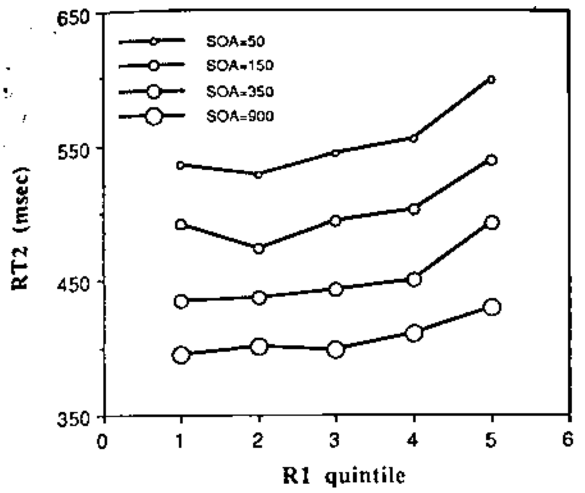

Figure 3. Experiment 1: Mean first- and second-task reaction time (RT1 and RT2) for each stimulus onset asynchrony (SOA) as a function of the quintile of the RT1 distribution in which RT1 fell. (R1 denotes first-task response.)

We performed an analysis of variance (ANOVA) on RT2 with RT1 quintile and SOA as variables. The effect of RT1 quintile was significant, $F(4, 64) = 32$, $p < .001$. The effect of RT1 quintile increased as SOA decreased, and their interaction was significant, $F(12, 192) = 3.6$, $p < .001$.

To examine further the dependence between RT1 and RT2, and the effects of SOA on any such dependence, we performed the following computation for each subject and SOA. For the first two blocks of the experiment, we found the Pearson product-moment correlation coefficient for RT1 and RT2 (correct trials only). Next, we found the coefficient for the third and fourth block, and so on. These coefficients were then averaged across subjects to yield an overall coefficient for each SOA. The coefficients are .29, .22, .21, and .12 for SOAs of 50, 150, 350, and 900 ms, respectively. The effect of SOA was significant, $F(3, 48) = 5.8$, $p < .01$, paralleling the quintile analysis.

Discussion

Experiment 1 revealed interference that was qualitatively similar to that found in other dual-task studies (e.g., Pashler & Johnston, 1989). As SOA was reduced from 900 ms to 50 ms, the average RT1 remained virtually constant, dropping only from 460 ms to 453 ms over this range. On the other hand, RT2 increased substantially as SOA was shortened (this is known as the *psychological refractory period* [PRP] effect). Between SOAs of 150 and 50 ms, RT2 increased by 50 ms. Experiment 1 clearly shows that interference occurs in a dual-task situation even when both responses are made to the same object.

Though interference certainly exists between the two tasks used in Experiment 1, it is rather mild: The slope of the function relating RT2 to SOA is only -0.5 between SOAs of 50 and 150 ms. For this reason, it seems reasonable to consider the possibility that counter to the bottleneck model, the responses are selected simultaneously in the single-object case, but at slowed rates. This amounts to a form of capacity sharing. Capacity-sharing models assume that many stages of processing draw on common resources and that processing of any given stage is slowed as more processes draw on the common pool of resources (Kahneman, 1973). A simple version of capacity sharing would claim that all processes rely on the same pool of resources, so the efficiency of processing on a given stage is determined solely by the total amount of processing concurrently operating, without regard for the type of processes that are active (Kahneman, 1973; P. McLeod, 1977). This theory has been rejected by a variety of data, some of it mentioned in the introduction (see Pashler, 1989; Pashler & Johnston, 1989). These data, however, have involved responses to more than one object, so their conclusions might not apply to the present situation. On the basis of this earlier work, however, it is clear that any capacity sharing between the two tasks in the present case is restricted to response selection. We next consider more closely the pattern of results we would expect given a bottleneck model.

Predictions of bottleneck models of dual-task interference. Precise predictions for the effects of SOA on dual-task performance follow directly from bottleneck models. The crucial observation is that according to a bottleneck model, varying SOA effectively manipulates the probability of postponement: The selection of the second response (R2) will have to wait for the completion of the selection of the first response (R1). Consider an SOA so long that postponement never occurs. According to bottleneck models, processing for the two tasks will proceed basically in parallel (though perhaps not independently). Thus the speed of R2 will not greatly depend on the relative speed of R1 (Pashler, 1989). In particular, the function that relates RT2 to the relative speed of R1 in our quintile analysis should be almost flat for long SOAs (Figure 3). The situation is much different at short SOAs, however. Consider the particular case in which SOA is so short that postponement always occurs. Reducing SOA will increase RT2 by the amount of the SOA reduction because S2 will be presented earlier (in relation to S1), but R2 selection still cannot proceed until R1 is selected. This will show up as a -1 slope of RT2 as a function of SOA at small SOAs (Welford, 1952, 1980) (Figure 2). Because R2 selection will always wait for R1 selection (at these very short SOAs), RT2 will depend heavily on the relative speed of R1; in fact, any delay in R1 will result in an equal delay of R2. Thus in our quintile analysis (Figure 3), RT2 as a function of R1 quintile should have a slope of 1 for short SOAs. Finally, at intermediate SOAs, postponement will occur on some trials only. Thus at these SOAs, RT2 will depend on the relative speed of R1 on the slower R1 trials only (where the majority of the postponement trials lie). In our quintile analysis (Figure 3), this should result in a curve that is flat at the left end and curved upward at the right.

On the basis of this discussion, three patterns of effects can be taken as diagnostic of bottleneck models. First, as SOA is reduced, the slope that relates RT2 to SOA should approach a -1 slope. Note that the SOA at which the -1 slope is achieved depends on the particular tasks used. For some pairs of tasks, even a bottleneck model might not predict a -1 slope unless negative SOAs are used. The second diagnostic is that the effect of SOA on RT2 should interact with R1 quintile. Third, the slope of RT2 plotted against RT1 in the quintile analysis should approach 1 at the short SOAs. Other models, such as capacity-sharing models, do not obviously make these predictions. In fact, to make capacity-sharing models predict this pattern of results, one has to make assumptions that make them look very much like bottleneck models (for a fuller discussion of capacity-sharing models vs. bottleneck models, see Pashler & Johnston, 1989).

Implications of the present results. The present experiment does not provide strong evidence to rule out capacity sharing when two responses are made to a single object. The slope of RT2 as a function SOA was -0.5 between 50 and 150 ms. This mild slope is consistent with a bottleneck model if one assumes that postponement did not always occur over the 50-150-ms range of SOAs. This might happen if selection of the naming response (R1) was very quick, a plausible hypothesis. But the slope is also consistent with capacity-sharing models. The slope of RT2 at a 50-ms SOA plotted against RT1 in the quintile analysis was somewhat steeper: 0.8. Though steeper than expected under a capacity-sharing model, this slope nevertheless does not rule out all capacity-sharing models.

The interaction of R1 quintile and SOA on RT2 was significant. But inspection of Figure 3 shows that it was not a large interaction (as one would expect under a bottleneck model). One possible reason for the modest of effect of SOA on this dependency is that the response is vocal, and the time to select a vocal response may be small and may vary little from trial to trial. With quick R1 processing, the selection of R2 may avoid postponement even at small SOAs. In this case, only the slowest of the R1 trials will result in postponement of R2, and thus weak dependencies will be found. Moreover, if the variance of postbottleneck stages in the first task is large compared with the variance of bottleneck stages, then variability in R1 will reflect motor variance more than response-selection variance. Thus, postponement trials will be spread fairly evenly across the R1 distribution rather than occurring mostly on the slow R1 trials, as assumed in the previous discussion. This would wash out any effect of SOA on the RT2-RT1 dependency.

The data definitely indicate substantial dual-task interference in responses to different attributes of the same object. This interference is consistent with a bottleneck at response selection, but capacity sharing between R1 and R2 selection is not ruled out. (No slowing of R1 was found as SOA was reduced, suggesting that any capacity sharing could not be of the symmetric form postulated by P. McLeod, 1977, for instance.)

Experiment 2

Experiment 2 examines further whether a bottleneck occurs in dual-task situations in which both responses are made to the same object. This experiment included both within-object and between-object conditions. In the within-object condition, the task and stimuli were the same as in Experiment 1 (subjects named the letter and made a button press to its color). In the between-object condition, the task and stimuli were the same except that S2 was a colored disc rather than the color of the letter. Assuming that making two responses to the same object results in capacity sharing between the response selections of the two tasks (rather than a bottleneck), the within-object condition should result in a markedly different pattern of effects from the between-object condition. Another possibility is that both within-object and between-object cases might result in a bottleneck, but with a qualitative processing difference between the two cases (e.g., the bottleneck might encompass fewer stages in the within-object case). This account would also predict substantial differences in the pattern of effects for within-object and between-object trials. This experiment addressed another possible objection to Experiment 1: Because the attributes of color and form were presented at different times, subjects were unable to treat them as part of the same object. Perhaps when attributes are presented at different times, they effectively constitute two different objects. For this reason, a 0-ms SOA condition in which the letter has its color from the start was included in the present experiment. But it is also conceivable that any advantage for the 0-ms SOA condition will occur only when the subject can predict that it will be a 0-ms SOA trial. Therefore, we considered the effects of blocking SOA and object conditions.

Method

Subjects. Sixteen undergraduates at the University of California, San Diego, took part in partial fulfillment of a course requirement.

Apparatus and stimuli. The apparatus and stimuli were the same as in Experiment 1 except that the letters were somewhat smaller: 1.5 cm in height and 0.5 cm in width. Red and blue dots with 0.9-cm diameter were also used as stimuli in this experiment.

Design. The experiment consisted of 12 experimental blocks and 1 practice block of 60 trials. The practice block and eight of the experimental blocks were mixed-trial blocks. In each of these blocks, every combination of the four SOAs (0 ms, 100 ms, 350 ms, and 900 ms) and the two object conditions (within- vs. between-object) occurred six times. The other 12 trials in each of these blocks were catch trials. The remaining four blocks of trials contained only trials with a particular SOA and object condition (except the 12 catch trials). For each subject there was a block of 0-within trials (0-ms SOA, within-object trials), 0-between trials, 100-within trials, and 100-between trials. The blocked trial blocks always occurred on Blocks 2, 5, 8, and 11. The 0-within block was always separated from the 0-between block by 6 blocks, half of the time appearing earlier in the session, and likewise for the 100-within and 100-between blocks.

Procedure. There were three basic trial types in the present experiment: within-object trials, between-object trials, and catch trials. The within-object trials were identical to the trials in Experiment 1 except that the letter was presented 1.2 cm above the fixation point on half of the trials and the same distance below the fixation point on half of the trials. The between-object trials differed from the within-object trials in that the letter did not change color, and instead a red or blue disc was presented on the opposite side of fixation from the letter. The subjects were instructed to respond to the color of the disc on these trials in the same way as they would respond to the color of the letter. The catch trials differed from the other two trial types in that no color was ever presented. Subjects were instructed to make only the naming response on these trials. There was no way for subjects to know which of the three trial types was occurring until the color was presented (or not presented), unless it was a blocked trial block.

The only other difference from Experiment 1 was a change in the instructions: Subjects were not coached on the order of the responses In the present experiment as they were in Experiment 1 but were told only to make both as quickly and accurately as possible. It was hoped that the catch trials would discourage subjects from grouping their responses and thus artificially elevating RT1 on some trials.

Results

For every combination of SOA x Object condition, we recorded 768 trials (16 subjects x 48 trials at each SOA x Object condition). Trials in which either response was quicker than 150 ms or slower than 1,800 ms were not included in the analysis. Mean RT on catch trials was 525 ms and 552 ms for mixed and blocked blocks, respectively. Both of these scores were in the range of RT1 on the other trials. Figure 4 shows mean correct RTs as a function of SOA, object, and blocking for both responses. Between SOAs of 100 and 0 ms, RT2 slowed by 75 and 72 ms for the within-object and between-object conditions, respectively; this corresponds to slopes of -0.75 and -0.72. The blocking variable does not seem to change this situation much.

Unlike in Experiment 1, the effect of SOA on RT1 was significant, $F(3, 45) = 14$, $p < .001$. The effect, however, was not large: RT1 at all four SOAs fell within a 46-ms range (516-562 ms). The effect of object condition was significant, $F(1, 15) = 11$, $p < .01$, as was the interaction of object condition and SOA, $F(3, 45) = 3.0$, $p < .05$.

As expected, the effect of SOA on RT2 was significant, $F(3, 45) = 99$, $p < .001$. The effect of object was significant, $F(1, 15) = 5.4$, $p < .05$, but all of the effect is found at the longer two SOAs (in which the within-object condition is slower than the between-object condition). The interaction of object and SOA was significant, $F(3, 45) = 16$, $p < .001$.

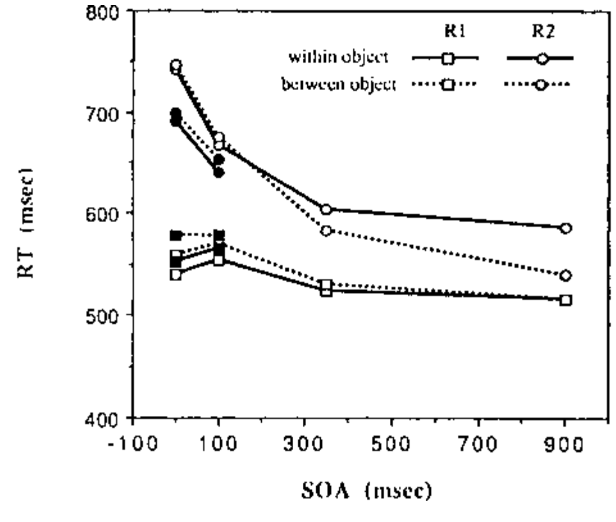

Figure 4. Experiment 2: Mean first- and second-task reaction time (RT) as a function of stimulus onset asynchrony (SOA), object condition, and blocking. (Open symbols indicate mixed-trial blocks. Solid symbols indicate blocked-trial blocks.)

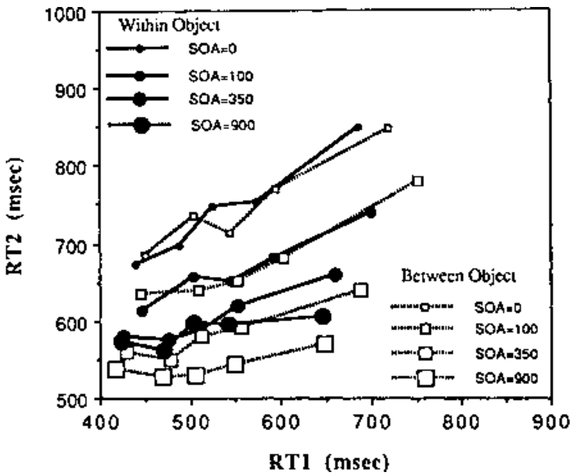

Figure 5. Experiment 2: Mean first- and second-task reaction time (RT1 and RT2) for each stimulus onset asynchrony (SOA) and object condition as a function of the quintile of the RT1 distribution in which RT1 fell.

We performed a separate analysis for the smaller two SOAs, with blocking as a variable. For RT1, object condition was again significant over this range, $F(1, 15) = 7.7$, $p < .05$, but there was no SOA x Object interaction, $F(1,15) < 1$. Blocking was significant, $F(1, 15) = 9.9$, $p < .01$, but it did not interact with SOA or object, both $F(1, 15) < 1$. For RT2, object was not significant over this SOA range, nor did it interact with SOA, both $F(1, 15) < 1$. Blocking did have a significant effect, $F(1, 15) = 12$, $p < .01$, but it did not interact with SOA, $F(1, 15) = 3.4$, $p > .05$, or object, $F(1, 15) < 1$.

The manual error rates on mixed-trial blocks were 3.2%, 3.1%, 4.3%, and 5.0% for SOAs of 0, 100, 350, and 900 ms, respectively. There was no effect of either SOA, $F(3, 45) = 2.3$, $.05 < p < .10$, or object, $F(3, 15) = 2.1$, $p > .15$, nor was there an SOA x Object interaction, $F < 1$. The manual error rates for blocked trial blocks were 3.9% and 3.6%, for SOAs of 0 and 100 ms, respectively. There was no effect of SOA ($F < 1$), object, $F(1, 15) = 2.9$, $p > .10$, nor was there an interaction of these variables ($F < 1$).

The quintile analysis for this experiment (as in Experiment 1) is shown in Figure 5. The effect of quintile and the interaction of quintile and SOA were significant, $F(4, 60) = 32$, $p < .001$, and $F(12, 180) = 5.4$, $p < .001$, respectively. Most important, object did not interact with quintile, $F(4, 60) = 1.5$, $p > .2$, and there was no three-way SOA x R1 Quintile x Object interaction, $F(12, 180) = 1.3$, $p > .15$.

Discussion

The results of Experiment 2 were quite similar to those of Experiment 1. Whereas RT1 varied little with SOA, RT2 was slowed dramatically as SOA decreased (the PRP effect). In addition, RT2 was highly dependent on the relative speed of R1, and this dependence was stronger at the smaller SOAs. Experiment 2 included shorter SOAs than were found in Experiment 1 (0 and 100 ms vs. 50 and 150 ms). As would be expected under a bottleneck model, this resulted in a steeper slope of the function relating RT2 to SOA (-0.5 in Experiment 1, -0.75 in the within-object condition of Experiment 2). Presumably, with further reduction of SOA we would get a -1 slope. Thus the data are consistent with a bottleneck model of dual-task interference for the within-object condition, as argued in the *Discussion* section of Experiment 1.

The results strongly support the hypothesis that a response-selection bottleneck occurs in dual-task processing regardless of whether the stimulus information comes from one object or two. If selection of responses to two attributes in the same object could proceed concurrently, we should have observed less interference between the two tasks in the within-object condition. In fact, RT2 for the two conditions differed by only 6 and 9 ms for SOAs of 0 and 100 ms, respectively (Figure 4). The effects of SOA were virtually identical. The dependencies of RT2 on the relative speed of R1 (at small SOAs) in the within-object condition was virtually identical to those in the between-object condition (Figure 5). Finally, the amount of interaction between SOA and R1 quintile was very similar in the two conditions (Figure 5). Thus, by every index, the interference between the two tasks is identical whether S1 and S2 are in the same object or in different objects.

Some aspects of the data did differ depending on whether the stimulus information came from one object or two different objects. At the longer SOAs (350 and 900 ms), RT2 was slower in the within-object condition than in the between-object condition. If the duration of bottleneck processing were different in the two conditions, then the effect would have been seen equally at all SOAs. Moreover, if anything we would expect bottleneck processing to be quicker in the within-object condition, but the effect went the other way. Thus a difference between bottleneck processing in the two object conditions does not account for the effect of the object condition at the long SOAs. The most likely explanation of the effect of object on RT2 is that subjects are quicker to notice the onset of a colored disc (S2 in the between-object condition) than a change of color of a letter (S2 in the within-object condition). Thus at the longer SOAs, in which some stages of processing of the second task might not begin (sometimes) until S2 has been noticed, the within-object condition will be slower on average, even though the bottleneck processing is identical. The object variable also had a small but significant effect on RT1. Though it is not clear why this effect occurred, it does not appear to be the result of slower R1 selection on the between-object trials. If it were, then R2 selection would begin later on average in the between-object trials. Thus a difference between within-object and between-object trials would be found on RT2 at the short SOAs. But as previously noted, RT2 was not affected by the object variable at the short SOAs. The critical observation is that RT2 in the within-object condition is strikingly close to RT2 in the between-object condition (at 0- and 100-ms SOA). Any difference in bottleneck processing should have at these SOAs. But none did. Thus we conclude that bottleneck processing is unaffected by whether the stimulus information comes from one object or two.

One might suppose that whether or not a processing bottleneck occurs in dual-task performance depends on how the subject prepares for the task. Perhaps under some task situations it is inefficient to perform two selections at once, so before performing the task the subject sets up some processing machinery to postpone any work on the selection of the second response until the first has been selected. In other situations, two selections might be made at once quite efficiently. Suppose that making two selections on the same object is efficient, but making two selections based on different objects or on one object when one of the attributes is not present from the start (as in the positive-SOA trials) is not efficient. A processing bottleneck might then be observed in the within-object condition of Experiment 2 (on mixed-trial blocks) only because on every trial the subject must be prepared for the between-object trials (and positive-SOA trials) as well as the within-object trials. If this were the only reason a processing bottleneck were occurring on the within-object trials, then when all of the trials in a block were within-object 0-ms SOA trials, much less interference should be found than when all trials in a block are between-object 0-ms SOA trials. Experiment 2 included such blocks of trials (Figure 5, solid symbols). Within-object trials were only 7 ms faster (not significant) on average than between-object trials on blocked 0-ms SOA blocks. Moreover, blocking does not seem to alleviate interference much. It is likely that most of the effect of blocking on RT2 results from subjects making R2 before R1 on some trials, hence the slight elevation of RT1 on blocked trials. One can conclude that having to prepare for between-object and positive-SOA trials is not the reason a processing bottleneck occurs in the within-object condition of Experiment 2.

Experiment 3

The preceding experiments examined the case of color and letter identity only. To examine the generality of our conclusions with regard to other elementary stimulus features, in Experiment 3 we required responses to be made with regard to the color and direction of motion of a solid disk. Perhaps response mechanisms can process the color and direction of movement of an object at the same time but not the color and name of a letter. If so, then the pattern of results of Experiment 3 should look much different from those of Experiments 1 and 2.

Method

Subjects. Twelve students at the University of California, San Diego, participated: 9 were undergraduates who participated in partial fulfillment of a course requirement, 2 were graduate students in the psychology department, and the remaining subject was chosen from a pool of paid subjects who participated in several experiments for 4 hr for $20.

Apparatus and stimuli. The apparatus was identical to that used in the previous experiments. The stimuli were 0.9-cm diameter circles that were either red or blue. These stimuli were also put into motion in one of the vertical directions. The details of how the stimuli were moved will be presented in the *Procedure* section.

Design. The experiment consisted of 1 practice and 14 experimental blocks of 48 trials. Every block included four SOAs (28, 100, 300 and 800 ms) separating the onset of the stimulus and the movement of the stimulus. Two colors (red and blue) and two movement directions (up and down) were used, and along with SOA these two variables were balanced and the order of presentation randomized within each block. Thus each combination of SOA, color, and direction occurred exactly three times within each block.

Procedure. Trials were initiated with the presentation of a white plus sign for 1,000 ms in the center of the screen as a fixation point. Two hundred fifty milliseconds after the offset of the fixation point, the stimulus was presented at fixation. After the SOA, the stimulus moved up or down. The movement was achieved with three frames: The stimulus in each frame was offset from the stimulus in the previous frame by 0.32 cm, or 0.3° of visual angle on the basis of a typical viewing distance of 60 cm. The first frame was displayed at the beginning of the SOA interval. The second and third frames were displayed at the end of the SOA interval and 28 ms after the end of the SOA interval, respectively.

Subjects made two responses to the stimuli. The first response was a button press to the color of the circle. If the figure was red, the subject pressed the *B* key, and if it was blue, the *N* key. The RT for this response was measured from the onset of the stimulus. The second response was to say into the microphone "UP" if the circle moved up and "DOWN" if it moved down. The RT for this response was measured from the onset of the movement.

The subject received written instructions similar to those in Experiment 1 except that they were not specifically instructed on what order to make the two responses. Instead, they were told only to make both as quickly and as accurately as possible. If, however, during the practice session subjects tended to make both responses at once or to make the vocal response first, they were told not to delay the manual response for the vocal response.

Results

The mean correct RTs for both responses are shown in Figure 6. For each SOA, we recorded 2,016 trials (12 subjects x 168 trials per subject). Responses faster than 150 ms or slower than 1,800 ms were not included in the analysis.

The data from the present experiment were very much like the data from the previous experiments, except that RT1 was strongly affected by SOA. Between SOAs of 28 and 300 ms, R1 was slowed by 60 ms on average, and even more dramatic slowing occurred between SOAs of 300 and 800 ms. This effect of SOA on RT1 was significant, $F(3, 33) = 12.1$, $p < .001$. But note that RT1 was slowed as SOA was increased rather than as it was decreased. The effect of SOA on RT2 was also significant, $F(3, 33) = 47$, $p < .001$. Between SOAs of 100 and 28 ms, R2 was slowed by 62 ms, resulting in a -0.86 slope over this range of SOAs.

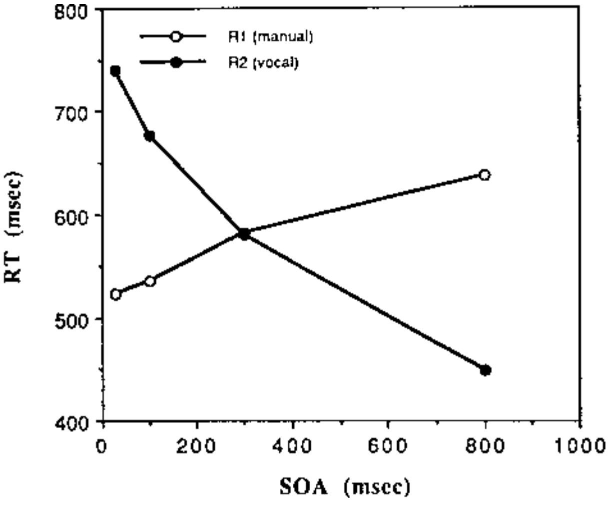

Figure 6. Experiment 3: Mean first- and second-task reaction time (RT1 and RT2) as a function of stimulus onset asynchrony (SOA). (R1 and R2 denote first- and second-task responses, respectively.)

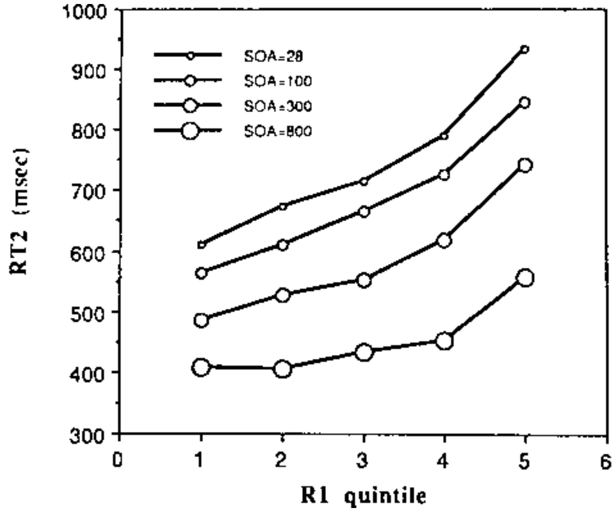

Figure 7. Experiment 3: Mean first- and second-task reaction time (RT1 and RT2) for each stimulus onset asynchrony (SOA) as a function of the quintile of the RT1 distribution in which RT1 fell. (R1 denotes first-task response.)

The error rates for the first task were 7.4%, 6.6%, 3.8%, and 3.4% for SOAs of 28, 100, 300, and 800 ms, respectively. The effect of SOA on these rates was significant, $F(3, 33) = 10$, $p < .001$. But more conservative R1 responding at the short SOAs could only have made the slope of RT2 as a function of SOA steeper.

We performed a quintile analysis as in the first two experiments, and the results are shown in Figure 7. The relative speed of R1 had a significant effect on RT2, $F(4, 44) = 55$, $p < .001$. Moreover, this variable interacted with SOA, $F(12, 132) = 9.4$, $p < .001$, indicating that the effect of R1 speed on RT2 is stronger at the short SOAs.

The correlation coefficients as computed in the previous experiments were .67, .67, .61, and .33 for SOAs of 28, 100, 300, and 800 ms, respectively. The effect of SOA was significant, $F(4, 56) = 5.8$, $p < .01$.

Discussion

The results for the present experiment are very similar to those for the previous two experiments, with one exception. Unlike Experiments 1 and 2, R1 slowed significantly as SOA increased. This is not a sign of capacity sharing. Recall that capacity sharing would yield more R1 slowing as SOA is reduced. In the present experiment, as SOA is reduced, the slowing of R1 decreases. For this reason, the effect of SOA on RT1 is probably due to subjects' strategy choices rather than limitations on processing. Specifically, the slowing is compatible with some subjects on some trials delaying execution of R1 until R2 is ready to be executed. This is what Pashler and Johnston (1989) termed *conjoint responding.*

Despite the effects of SOA on RT1, the slowing of R2 is similar to that in the previous experiments. Between SOAs of 28 and 100 ms, RT2 reached a slope of -0.86. If RT1 had been flat, this slope would mean that little or no processing occurs on R2 during the stages of interference. What does the slope mean in the present case, in which R1 is slowed at the longer SOAs? Two cases are possible. First, perhaps only R1 processing stages that are after the interference between the two tasks are delayed at the long SOAs. In this case, the effects of SOA on RT2 can be interpreted as if R1 was flat because these later stages do not interfere with R2 processing. But perhaps some stages of R1 that interfere with R2 processing are delayed at the long SOAs. If so, then the slope found on RT2 is not as steep as would have occurred if these stages were not delayed, because RT2 at long SOAs would be escalated. So if anything, the -0.86 slope found in Experiment 3 is an underestimate of the true slope.

In Experiments 1-3, we tested the possibility that making two responses to a single object can circumvent the bottleneck. No evidence that this is so has been found.[2] In all three experiments, the interference between the two tasks seems very much like standard dual-task interference. It seems clear that the interference in the dual-task situation does not depend on whether the responses are made to separate objects. This is exactly what one would expect if the interference occurs because some mechanism necessary for selection of responses can only select one response at a time, regardless of the perceptual configuration of the stimuli that determine the responses.

Responses to the Same Attribute of an Object

What is it that the bottleneck mechanism can only do one of at a time? In the preceding section we saw that bottleneck interference arose even when only one object was present. This argues that the limit is not an inability to initiate processing on more than one object at a time. In this section, we examine another nontraditional dual-task situation: one in which both responses (one manual and one vocal) are determined by the same attribute of an object. Such responses will be called *redundant responses* because the correct choice for one response implies the correct choice for the other. We begin by considering—in the abstract—four seemingly plausible processing models for the redundant-response case. We then consider the broader theoretical significance of this issue in more depth.

The Sequence of Processing in a Redundant-Response Task

Figure 8 shows four alternatives for the sequence of processing that occurs in a redundant-response dual-task situation. Here and in later discussions, response selection is assumed to be the bottleneck processing stage (Pashler & Johnston, 1989).[3]

First, as in the usual dual-task situations, each response may require a separate response selection (despite the redundancy). We refer to this hypothesis as *serial selection* (Figure 8a). If this hypothesis is correct, then on any given trial, one response (depending on which response is selected first) will be slowed compared with when it is made alone, whereas the other will not be slowed.[4] Note that this model corresponds to the model of processing for the standard dual-task situation shown in Figure 1.

A different possibility is that the responses are selected in parallel. We call the simplest version of this *independent selection* (Figure 8b). According to this second hypothesis, slowing of either response (compared with the single-task case) would result from a general cost of parallel processing. Investigations of ordinary (nonredundant) dual tasks have provided no evidence for such parallel selections, but that does not rule it out here. A slightly more complicated version of parallel selections would propose that responses are selected separately as in the independent-selection model but then are initiated simultaneously. We call this third hypothesis *synchronized parallel selection* (Figure 8c).[5] By this account, whichever response would have been faster in the single-task case will be slowed when made with the other response because it must wait for the slower response to be selected before it is initiated. Thus, the larger the difference between the durations of vocal and manual response selection, the greater the slowing would be.

Finally, perhaps only one response selection occurs, but the response selected is actually a conjunction of two actions—one vocal and one manual. We call this fourth hypothesis *conjoint selection* (Figure 8d), which is to be distinguished from the conjoint responding mentioned previously. In this case, each response would be slowed by the difference between the duration of the conjoint selection and the duration of the single-task selection for that response. So, like the synchronized-parallel-selection model, this hypothesis entails that any slowing corresponds to a difference between the durations of two response selections.

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[2] Stephen Monsell (personal communication, November 8, 1990) has found that certain compatible responses do not seem to show much interference. In his experiment the responses were made to the same object, but the more important factor in his demonstration was probably the level of practice and the responses used rather than the stimulus arrangement. The same applies to Schvaneveldt (1969). Regardless, the present results show that making the responses to a single object is not sufficient to avoid interference.

[3] The arguments that follow do not depend on the correctness of this assumption. But they do depend on the well-justified assumption that response-selection manipulations affect the duration of bottleneck processing (Pashler & Johnston, 1989).

[4] Notice that in the redundant-response paradigm, we cannot vary SOA because both responses are made to the same thing. The next best analysis is to compare single-task RT (corresponding to RT at very large SOA) with dual-task RT (corresponding to RT at 0 SOA).

[5] The final stage in this postulated sequence is just the response grouping sometimes observed in standard dual-task paradigms (conjoint responding; see Pashler & Johnston, 1989).

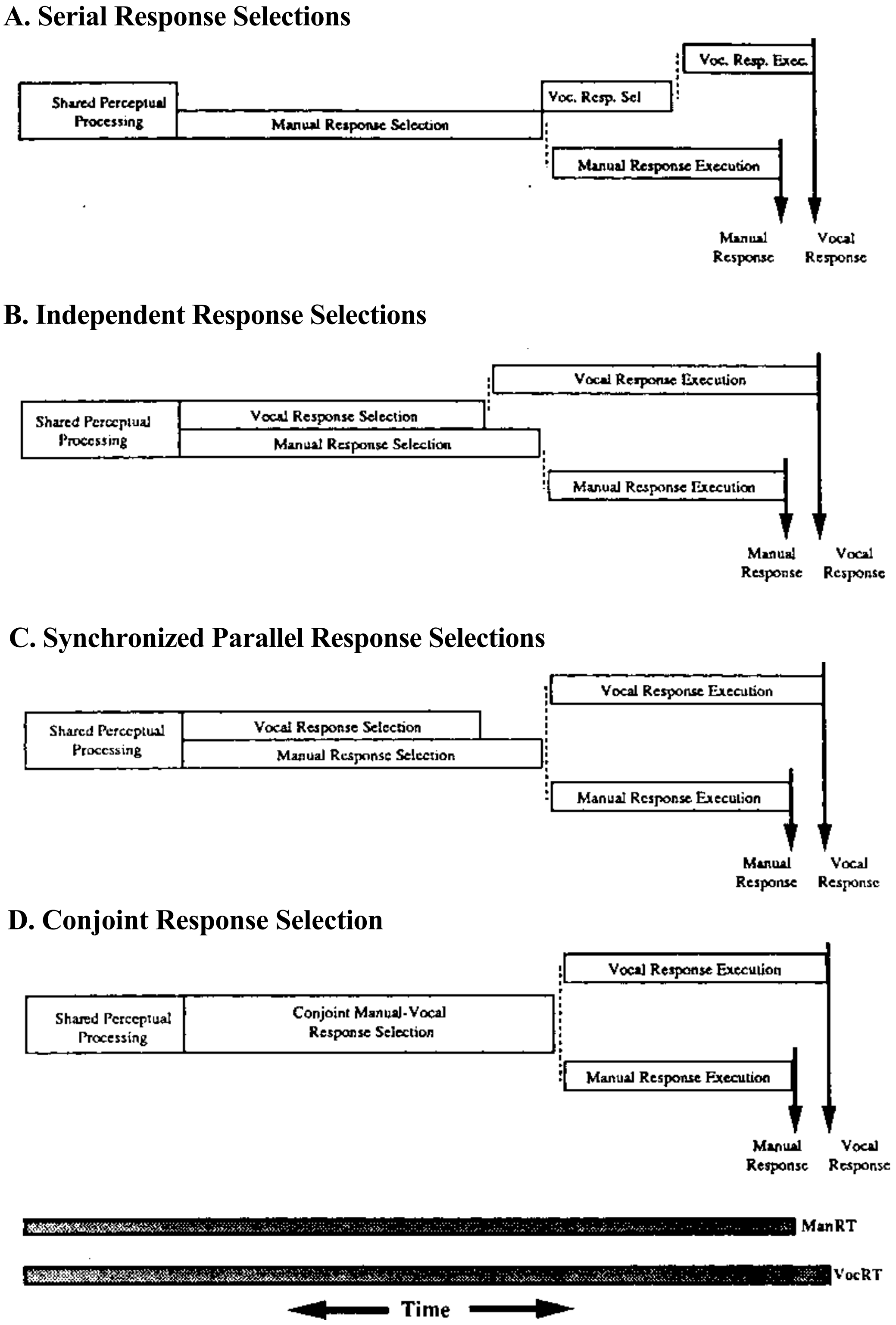

Figure 8. Four possibilities for how response selections occur for redundant responses (see text). (Part A, serial selection: Response selections are made for each response, one at a time. Part B, independent selection: Response selections are made for each response simultaneously. Part C, synchronized parallel selection: Response selections are made in parallel, but responses are not initiated until they are both selected. Part D, conjoint selection: One response selection is made for both responses, but the response that is selected is a conjunction of two actions. RT denotes reaction time.)

The Nature of the Bottleneck and the Sequence of Processing in the Redundant-Response Case

Thus far we have considered four possible models for the sequence of processing in a redundant-response dual-task paradigm. We now consider the relation between these various models and the possible processes underlying the bottleneck. It has been suggested previously that the bottleneck arises because some mechanism cannot simultaneously carry out the work involved in the bottleneck stage of more than one of the tasks traditionally used in dual-task experiments. If this characterization is accurate, the critical challenge is to characterize the input to and the output of this mechanism. In the traditional dual-task situation, the inputs to the mechanism are necessarily separate for the two tasks, and so are the outputs. Thus, the mechanism is invoked twice.

It is possible that in the redundant-response paradigm, even though what is input to the bottleneck mechanism for each response is identical, the bottleneck mechanism must be invoked twice (once to select each response). If we assume that the output of the mechanism is restricted to a specification of a single motor action, this hypothesis would seem most natural. In this case, either the output of the mechanism, the processing required to produce this output, or both would be the limiting factor. This possibility is called the *simple action model of the bottleneck* (or just the simple action model).

The redundant-response paradigm provides a straightforward test of the simple action model. The simple action model clearly implies that serial selections (Figure 8a) must occur in the redundant-response situation. But more important, if serial selections do occur, it would constitute good evidence that the simple action model is correct: The processing required for the redundant-response task is the same as for a single-response task, with the single exception that two actions rather than one must be prepared and executed.

In contrast to an output limit, the real limit of the bottleneck mechanism may be related to its input. In Experiments 1-3 we rejected the possibility that the mechanism can select multiple responses so long as its input comes from a single perceptual object. Nevertheless, the limit still might lie entirely on the input to the mechanism, but only a single attribute rather than all of the attributes of a single object can be input at one time. Perhaps once the mechanism has received its input, it can select many responses simultaneously and independently. In the redundant-response case, the input to the bottleneck mechanism is presumably the same for both responses. Thus if the bottleneck arises only because of limits on the input to the mechanism, parallel selections would occur (Figures 8b and 8c).

Finally, perhaps even though the critical mechanism selects one response at a time, the functional response that it selects is not limited to a single "action," as we ordinarily use that term. Instead, responses that are selected may consist of an arbitrary assemblage of actions readied in advance through some preparatory activity. For such preparation to occur successfully, it might be necessary for only a few response pairs to be used, so the set of action pairs can be retained in some working memory. A simple redundant-response task would allow this, so a conjoint selection (Figure 8d) would be expected under these conditions. Conversely, if only a single response selection occurs in the redundant-response task, then the mechanism is obviously capable of selecting multiple actions under some circumstances.

Given these relationships between hypothetical causes for the bottleneck and the possible sequences of processing stages in the redundant-response experiment, it follows that if we can decide between the four processing models shown in Figure 8, we will have moved closer to understanding the underlying reasons for the bottleneck. In the General Discussion section we return to these broader questions.

A Previous Redundant-Response Experiment

Holender (1980) had subjects respond to the name of visually presented letters with a button response and a vocal naming response; the tasks were performed alone and together. He found that the manual response was essentially unaffected by whether it was made alone or with the vocal response but that the vocal response was slowed by 150 ms when done with the manual response. He also manipulated how frequently each stimulus was presented to the subject. Performed alone, only the manual response was affected by frequency. When done together, however, the responses were affected equally, and the effect was the same as for the manual response done alone. Holender concluded that the two responses are prepared separately and that the frequency manipulation affects the time to make the vocal response when it is made with the manual response because they are initiated together (similar to what we have called synchronized parallel selection; see Figure 8c). By this account, when the responses are performed together, the manipulation still affects only processing for the manual response. But because the vocal response tends to be prepared earlier, the initiation of the two responses is determined solely by when the manual response is ready. Hence any factor delaying the manual response will equally affect vocal RT.

Holender's proposal amounts to synchronized parallel selection (Figure 8c). The data could also fit the serial-selection model (Figure 8a), however, given that the manual response is always selected first. The 150-ms slowing of the vocal response in Holender's study is the same as the slowing between the longest and shortest SOAs of R2 in our Experiment 1, though much smaller than the 360-ms slowing found in our Experiment 3.[6] Thus the slowing is of roughly appropriate magnitude for the serial-selection model. Moreover, the propagation of the stimulus frequency effect onto the vocal response in the dual-task condition would be predicted by the serial response selections (Figure 8a). Holender's data are also consistent with conjoint selections (Figure 8d). The only model that his data would seem to contradict is the independent-selection model (Figure 8b).

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[6] The difference of RT2 at 0 SOA and long SOA is a rough estimate of the duration of R1 selection. In fact, if the duration of processing at each stage of the two tasks is the same, and if the durations did not vary, then this estimate would be exact.

Experiment 4

In Experiment 4, subjects named the color of a letter and made a three-alternative manual response (also to the color). This experiment is very similar to Holender's (1980). Holender's vocal task was to name a letter, and his manual task was a four-choice button press to the letter name. Thus, his vocal task was a particularly quick task, and his manual task was relatively slow. The present experiment used a more time-consuming vocal task (color naming), thus making the durations of the response selections of the two tasks more similar. If we find less slowing of the vocal response than Holender found, this would suggest synchronized parallel selections or a conjoint-selection model, because these hypotheses predict no more slowing than the difference between the durations of two response selections. But according to the serial-selection hypothesis, the magnitude of the vocal slowing is determined by the duration of the manual response-selection stage. Hence negligible slowing in the case of Experiment 4 would not be consistent with a serial-selection model. (It is not clear how an independent response-selection model would account for such a finding either, but this will not be pursued here because Experiment 5 bears more directly on the issue.)

Method

Subjects. Twelve undergraduates at the University of California, San Diego, participated in partial fulfillment of a course requirement.

Apparatus and stimuli. The apparatus and stimuli used in the present experiment were identical to those used in Experiment 1, except that the color of the letter did not change after it was presented, and letters appeared in green in addition to red and blue.

Design. The experiment consisted of 1 practice block, for which no data were recorded, and 12 experimental blocks of trials. There were three block types. In some blocks, subjects were required to make a manual response, and in others a vocal response was required, and in still others both responses were required. The specification of these responses is described in the *Procedure* section. Subjects made both responses for the practice block and were watched by the experimenter to ensure that they followed the instructions. The 12 experimental blocks consisted of the three block types occurring in a fixed sequence that was repeated four times. This sequence was counterbalanced across subjects. Every block had 45 trials. Each color appeared 15 times in every block, and the order of the colors was randomized.

Procedure. Before each block of trials, instructions that informed subjects of what responses to make were displayed for 2,500 ms. They were instructed to make manual responses only, vocal responses only, or both manual and vocal responses. The manual response required subjects to press the *B* key on the computer keyboard if the color of the stimulus was red, the TV key if the color was blue, and the *M* key if it was green. The vocal response required subjects to say the color name into the microphone. When both responses were required of the subject, they were informed with written instructions given to them before the experiment to make both responses as quickly and accurately as possible; they were not told in what order to make the responses. Thus, even when both responses were required, they were determined by the color of the stimulus.

Each trial began with the presentation of a white plus sign for 1,000 ms in the center of the screen as a fixation point. Two hundred fifty milliseconds after the offset of the fixation point, the stimulus letter appeared at fixation. It was chosen randomly from the 26 letters of the alphabet, and its color (red, blue, or green) was chosen randomly without constraint. The stimulus remained on the computer screen until the response(s) for the trial was made or 2,500 ms elapsed. If no response was detected after 2,500 ms, then the stimulus was removed, and the next trial commenced. Subjects were informed of incorrect responses by a tone at 800 Hz sounded for 300 ms. The intertrial interval, the time between the last response of a trial and the fixation point for the next, was 1500 ms.

Between blocks, subjects rested until they felt like continuing. During this period, the average RTs for both types of responses and for each preceding block were displayed to the subjects.

Results

The mean correct manual RTs were 551 and 553 ms for the single- and dual-task trials, respectively, and the vocal RTs were 572 and 595 ms. In all, 4,320 responses were recorded for each response type (12 subjects x 45 trials per block x 8 blocks requiring each type of response). Responses faster than 150 ms or slower than 1,800 ms were not included in the analysis.

Whether or not the response was made alone had different effects on vocal and manual responses. Manual responses were unaffected by whether they were made alone, $F < 1$. In fact, the difference between the mean for the manual response made alone and made with a vocal task was only 2.5 ms. The vocal response, however, was significantly slowed by being made with a manual response ($F < 1$). The slowing was small, however: an average of 23 ms. This is much smaller than the interference ordinarily encountered in dual-task situations, such as in Experiments 1-3.

More manual errors were made when the manual response was made alone (4.0%) than when it was made with the vocal response (1.4%), $F(1, 11)= 13.7$, $p < .01$. It is doubtful that more conservative manual responding when the responses are made together could account for the slowing of the vocal response because such slowing would more likely show up on the manual response (it did not).

We found high correlations between the RTs for each response when responses were made together. We computed the Pearson product-moment correlation for each dual-task block. These coefficients were averaged across blocks and subjects, yielding an overall correlation of .84.

Discussion

The results of the present experiment show one marked difference from those of Holender (1980). In both studies, the manual response did not suffer when combined with the vocal response, whereas the vocal response was slowed when combined with the manual response. Holender, however, reported a slowing of the vocal response by 150 ms when it was made with the manual response. In the present study, only a 23-ms slowing occurred. Presumably, the discrepancy arises because of the difference in tasks used in the two experiments. The manual response in the present experiment is faster than the manual response used by Holender (three-choice reaction to a color vs. a four-choice reaction to a letter). The vocal response of the present experiment, however, is slower than the vocal response used by Holender (color naming vs. letter naming).

The minuscule amount of slowing on the vocal response combined with the manual response makes it unlikely that subjects have to make two serial response selections when performing the tasks of the present experiment. If serial selections were made, then the vocal task when combined with the manual task would on average be delayed by the duration of manual-response selection. But this stage surely takes more than 23 ms. (Consider the magnitude of slowing observed in Experiments 1-3, all of which used similar responses.) This leaves two plausible possibilities for the dual-response condition: Either subjects make a single conjoint selection (Figure 8d), or they make two parallel selections (Figures 8b and 8c).[7]

Is vocal-response slowing due to occasional queuing? It is possible that the small slowing of the vocal response when made with the manual-response results from a tendency on some small portion of the trials to select the vocal and manual responses sequentially

If this were happening, then the slowest vocal RTs would disproportionately come from trials in which the responses were selected sequentially. Thus the offset of vocal RT from manual RT would be much larger for trials with the slowest vocal responses than for trials with intermediate and quick vocal responses. The mean latencies for manual and vocal responses for the dual trials are shown in Figure 9 as a function of the relative speed of the vocal response for the trial.[8] Notice that the offset of the manual RT from the vocal RT is virtually independent of the relative speed of the vocal response. Apparently, the vocal slowing does not result from a tendency to select the responses sequentially on some trials.

Experiment 5

Experiment 4 makes it clear that very little interference occurs between redundant manual and vocal responses. Serial selections (Figure 8a) are therefore unlikely, but several possibilities remain. One possibility is that independent selections (Figure 8b) are made for the responses used in Experiment 4, and the slight vocal slowing (23 ms) must therefore be the result of some (modest and one-way) interference. Another alternative is the synchronized-parallel-selection model (Figure 8c). According to this model, the slowing of the vocal response is the result of delaying its execution so that it can be initiated with the manual response. The final alternative is that subjects make a single conjoint selection (Figure 8d). In this case, the slowing results from the difference in duration between the conjoint selection and the selection of the single-task vocal response. The present experiment is aimed at ruling out independent selections.

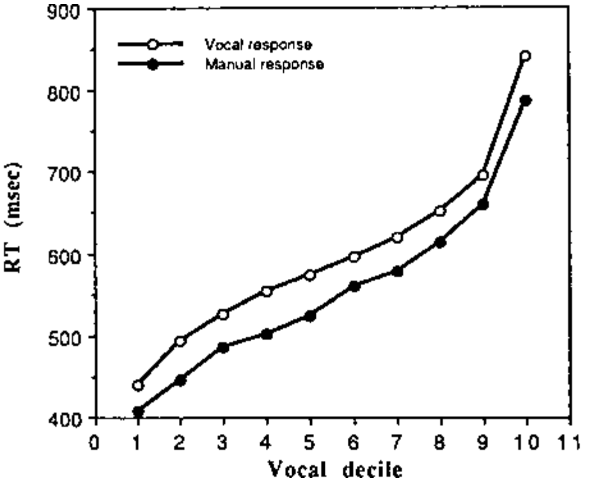

Figure 9. Experiment 4: The mean manual and vocal reaction times (RTs) of dual trials as a function of the relative speed of the vocal response (vocal-response decile).

In Experiment 5, subjects saw a colored letter and, as in the previous experiment, named the color, made a manual response to the color, or both. In addition, in the present experiment the compatibility of the position of the stimulus with the manual response was manipulated. A stimulus to the left of fixation is compatible with a left-button-press response and incompatible with a right-button-press response: This is the so-called Simon effect (Simon, 1969). For now, assume that (as common sense would suggest) this manipulation affects response selection for a manual response; in the General Discussion section we examine this issue more closely. If the effects of the Simon manipulation propagate onto the vocal task combined with the manual task, then the vocal slowing is not just a result of general interference between the two tasks, and thus an independent-selection model (Figure 11b) cannot account for the data. This would leave only the models shown in Figures 11c and 11d.

Method

Subjects. Twenty-five undergraduates at the University of California, San Diego, participated in partial fulfillment of a course requirement. One subject's data were not included in the analysis because he did not follow the instructions in one condition.

Apparatus and stimuli. The apparatus and stimuli used in the present experiment were identical to those used in Experiment 4.

Design. The experiment consisted of 12 experimental blocks and 1 practice block of 48 trials. Letters appeared in one of two colors (red or blue) and one of three positions (left, right, or center). Each combination of color and position appeared six times in each block, and the order of presentation of these conditions was randomized. The between-block factor of response type was determined precisely, as in the previous experiment.

Procedure. The procedure for the present experiment was identical to that used in Experiment 4 except that stimuli appeared in one of three locations: 3.2 cm to the right of fixation, 3.2 cm to the left of fixation, or at fixation. The distance from the leftmost to the rightmost stimulus location spanned 8.1 cm, or 7.7° of visual angle, for a typical viewing distance of 60 cm.

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[7] The independent-selection model (Figure 8b) is inconsistent with the high correlations between manual and vocal RT in the dual-task condition of this experiment. But Experiment 6 bears more directly on this model, so we will not eliminate it yet.

[8] Figure 9 shows that the vocal response was on average 30-50 ms slower than the manual response at all vocal response deciles. We checked to be sure that this does not indicate the voice key picking up the sound of manual keypress responses.

Results

Figure 10 shows for manual and vocal responses the mean correct RT as a function of the compatibility of the stimulus position with the manual response and whether the response was made alone or with the other response. For each Position Compatibility x Response Type combination, 1,536 trials were recorded (24 subjects x 64 trials per combination of position and response type). We performed three analyses on the RT data. We analyzed the vocal and manual responses with position compatibility and single versus dual trials as variables, and we analyzed dual trials with position compatibility and manual versus vocal response as variables.

Manual-response data. The manual response was not significantly affected by whether it occurred alone (444 ms) or with a vocal response (449 ms), $F(1, 23) < 1$. The position compatibility effect was significant, $F(2, 46) = 64$, $p < .001$. Most important, this variable did not interact with whether the response was performed alone or with a vocal response, $F(2, 46) < 1$. Thus the pattern of RTs for manual responses made alone and manual responses made with a vocal response are virtually identical.

Vocal-response data. The vocal response was again slowed when combined with the manual response (491 ms) compared with the single task (462 ms), $F(1, 23) = 25$, $p < .001$. Moreover, this variable interacted with position compatibility, $F(2, 46) = 5.9$, $p < .005$. This reflects the fact that position compatibility did not have any apparent effect in the vocal-response-alone condition: For the vocal response alone, the effect of position compatibility was nonsignificant, $F(2, 46) = 1.1$, $p > .3$. So although manual responses were quite unaffected by whether a redundant vocal response was also made, vocal responses were slowed by concurrent manual responses. Position compatibility, which did not affect vocal responses when made alone, slows vocal responses to the same degree as it slows manual responses in the dual-task condition.

Dual-response data. Unlike in the single-response trials, in the dual-response trials the position compatibility manipulation had an effect on both manual and vocal responses. The difference between incompatible and compatible positions was 33 ms and 25 ms in the dual trials for the manual and vocal responses, respectively. These effects were significant, $F(2, 46) = 32$, $p < .001$, as was the difference between these effects, because whether the response was manual or vocal interacted with position compatibility, $F(2, 46) = 5.5$, $p < .01$. So when both manual and vocal responses are required, position compatibility has an effect on both responses (though the effect may be slightly smaller on the vocal responses).

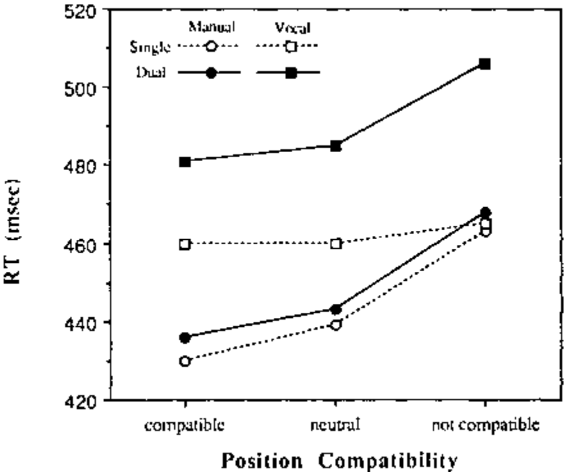

Figure 10. Experiment 5: Mean vocal and manual reaction time (RT) as a function of position compatibility and single versus dual tasks.

Correlations between the vocal and manual responses for the dual trials were found for each dual block. The mean correlations (Pearson product-moment) across subjects and blocks are .81, .86, and .83 for compatible, neutral, and incompatible blocks respectively. The effect of compatibility on the correlation coefficients was not significant, $F(2, 46) = 1.8, p > .15$.

Error data. The manual error rates for compatible, neutral, and incompatible trials, respectively, were 2.0%, 2.5%, and 4.7% in the single-response condition and 1.0%, 2.1%, and 2.2% in the dual-response condition. Errors occurred more frequently in single-response than in dual-response trials, $F(2, 46) = 18$, $p < .001$. Perhaps a speed-accuracy trade-off could explain the slight (though significant) difference between single- and dual-response conditions for manual responses. Significantly more errors were made when the position of the stimulus was incompatible than otherwise, $F(2, 46) = 8.1$, $p < .001$. The interaction of position of the stimulus and whether the manual response was made alone or with a vocal response was marginally significant, $F(2, 46) = 3$, $.05 < p < .06$.

Discussion

When the responses were performed alone, the compatibility of the position of the stimulus with the manual response affected the time to make the manual response but not the vocal response. When both responses were made together, however, this variable affected both, and roughly to the same degree. Moreover, whether the manual response was made alone or with the vocal response had no effect on the manual RT. Furthermore, the effect of position compatibility on the manual response was also the same whether or not it was made with the vocal response.

Completely independent selections of vocal and manual responses. Parallel selection of the vocal and manual responses (with a bit of general interference accounting for slight vocal slowing) is ruled out.

When the responses were made alone, the position compatibility manipulation had no effect on the vocal response, but it had a 33-ms effect on the manual response. From this we infer that position compatibility affects the processing for the manual response but not the vocal response. If when combined the responses were processed independently, with only a tiny bit of general interference, the vocal response would be only minimally affected by position compatibility when made with the manual response. Vocal RTs, however,

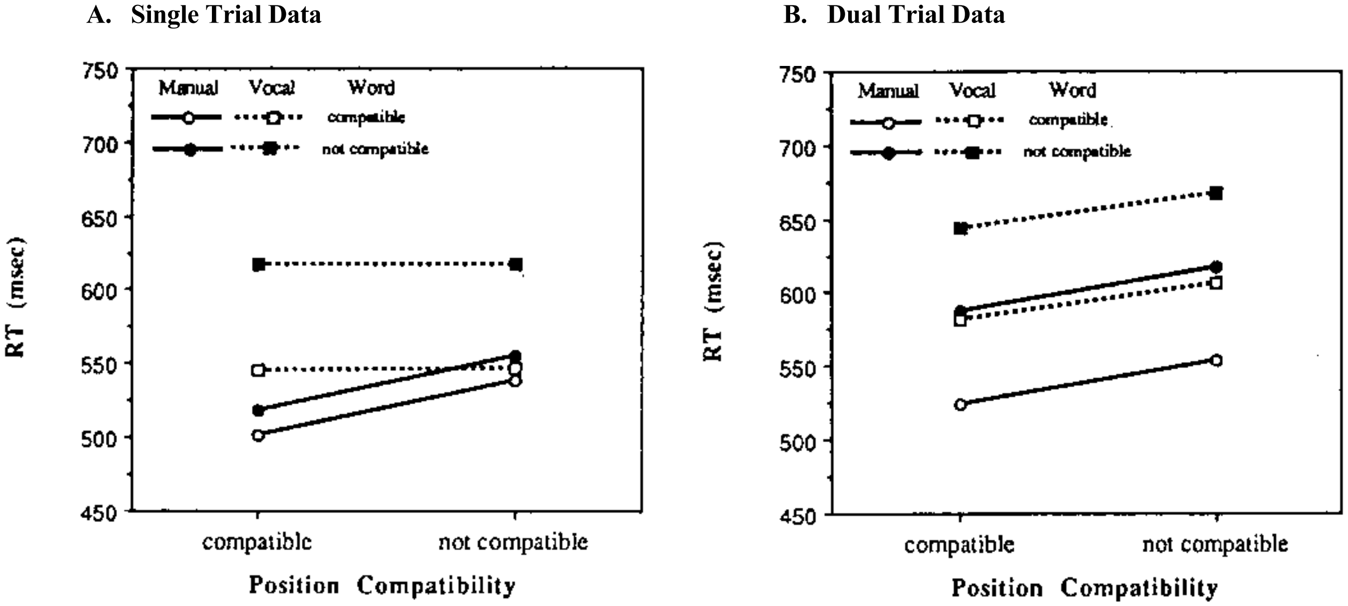

Figure 11. Experiment 6: Mean vocal and manual reaction time (RT) as a function of position and word compatibility for single-task (Panel A) and dual-task (Panel B) trials.

were slowed by 25 ms, paralleling a 33-ms effect in the manual dual-task condition. In addition, the correlations between vocal and manual RTs in the dual-task conditions of Experiment 4 and 6 were .84 and .83, respectively. This too does not seem likely for the independent-selection model.

How many response selections occur? The data are most consistent with the conjoint-selection model (Figure 11d). The propagation of the effect of the position compatibility manipulation onto the vocal response combined with the manual response shows that the processing for the two responses cannot be completely independent. Moreover, the synchronized-parallel-selection model (Figure 8c) predicts that the position compatibility manipulation will have a smaller effect on the manual response when it is made with the vocal response than when it is made alone, unless the vocal response is always selected more quickly.[9] According to the synchronized-parallel-selection model, the amount of slowing of the vocal response when made with the manual response should correspond to the difference between selection times for the two responses. The slowing in Experiments 5 and 6 was quite small: 23 and 29 ms, respectively. Because the selection times are variable, it seems unlikely that vocal selection would always be faster than manual selection. With this possibility discounted, it follows that if synchronized parallel selections are made, position compatibility should have a much smaller effect on the manual response when made with the vocal response than alone. But the effect on the manual response was 33 ms both when combined with the vocal and when alone, thus demonstrating that the effect in the two conditions cannot differ by very much. Therefore, synchronized parallel selections do not seem likely. Of course, this argument relies on accepting that this experiment had the power to detect the interaction. For this reason, in the next experiment we seek more evidence against synchronized parallel selections.

The locus of the effect of the position compatibility manipulation. So far it has been assumed that the position compatibility manipulation has its effect mostly on response selection, which seems to be the key bottleneck stage. The present experiment, however, provides evidence that the manipulation has an additional (but small) effect after the bottleneck. The effect of the manipulation when the vocal and manual responses were made together was 33 ms on the manual task and 25 ms on the vocal task. In fact, position compatibility significantly interacted with vocal versus manual response in the combined-response condition, $F(2, 46) = 5.5$, $p < .01$. It therefore seems likely that the manipulation has an effect on the manual response after common processing is complete and hence might have some slight extra effect after the response-selection bottleneck.

Experiment 6

The preceding experiment tested (not fully conclusively) whether two synchronized parallel response selections are made when subjects make two redundant responses to a single stimulus attribute (Figure 8c). If this model is correct, then the effect of the position compatibility manipulation on the manual response should have been smaller when combined with the vocal response than when the manual response was made alone (see the *Discussion* section of the preceding

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[9] This can be clearly seen symbolically. Let X, Y, and Z be positive random variables standing for the vocal-selection time, the manual-selection time, and the effect of the manipulation on the response-selection stage, respectively. Then the effect of the manipulation on manual RT on dual trials is $E(\max(X + Z, Y) - \max(X, Y))$ and the effect on manual-only trials is EZ. If X is sometimes smaller than Y, then $E(\max(X + Z, Y) - \max(X, Y)) < EZ$. Moreover, if X and Y are distributed about the same, the difference will be large.

experiment). In fact, the effect was not smaller, suggesting that parallel selections do not occur.

Experiment 6 provides a further test of the synchronized-parallel-selection model. As in the previous two experiments, subjects make manual, vocal, and combined responses to the color of stimuli appearing on the computer monitor. As in Experiment 5, the stimuli appear to the left or right of fixation. In the present experiment, however, the stimuli are the words "RED" and "BLUE." It is well known that saying the color of a color word is slower (generally by about 100 ms) if the color word does not correspond to the color to be named: This is the Stroop effect (Stroop, 1935). On the basis of previous research (reviewed by Dyer, 1973; C. M. McLeod, 1991), we expect that a manual-choice response will not be affected by the Stroop manipulation. We assume for the moment that the Stroop manipulation affects only the bottleneck mechanism (Experiment 7 provides direct evidence).

In the present experiment, we independently manipulate manual and vocal response-selection duration with the Simon manipulation and the Stroop manipulation, respectively. The synchronized-parallel-selection model specifically predicts that if these manipulations propagate onto both responses in the dual-task condition, then their effects must be strongly underadditive (see the following for details). Hence if we find no interaction between these two manipulations, it is strong evidence against parallel selections, and by eliminating this alternative, strong evidence for conjoint selection of redundant responses.

Method

Subjects. Twelve undergraduates at the University of California, San Diego, participated. Nine participated in partial fulfillment of a course requirement, and the remaining 3 were chosen from a pool of paid subjects who participated in several experiments for 4 hr for $20.

Apparatus and stimuli. The apparatus was the same as that used in the previous experiments. The stimuli were the words "RED" and "BLUE," which appeared in either the color red or the color blue.

Design. The design of the present experiment was similar to the previous two experiments. In the present case, however, there were 18 experimental blocks instead of 12, and each block consisted of only 32 trials. Included were the variables of stimulus position (left of fixation and right of fixation), word ("RED" and "BLUE"), and color (red and blue). Each combination of the three variables occurred four times in each block, and the order of presentation was randomized. The response type for each block was determined by the same procedure as in the previous two experiments.

Procedure. The procedure differed from the previous experiment on two points. First, the stimuli were presented in only two locations, 3.8 cm to the left or right of fixation. Second, the subjects were given two types of warnings between trials. If on a manual-response block a sound was detected by the voice key, or if on a vocal-response block a keypress was made, a message warning the subject to make only the appropriate response was displayed on the computer monitor. This helped ensure that subjects were following the instructions.

Results

Figure 11 shows the mean correct RT for manual and vocal responses as a function of position and word compatibility for single- (Figure 11a) and dual-task (Figure 11b) trials. For each compatibility, task (single vs. dual) and response type (manual vs. vocal) combination, we recorded 576 RTs (12 subjects x 6 blocks x 8 RTs). Subjects made manual-response errors on 2.4% of the trials. There were no significant main effects or interactions on error rates.

The most important result is that the position and word compatibility manipulations were, with only minuscule deviations, completely additive: $F(1, 11) < 1$, for the dual-task responses. For this reason, effects of these variables will be pooled when they are reported. As in the previous experiment, we performed separate analyses on the vocal, manual, and dual RT data.

Manual-response data. As expected, the position compatibility manipulation had virtually the same effect on the manual response whether it was made alone or with the vocal response. On the other hand, the word compatibility manipulation significantly affected the manual response only when it was combined with the vocal response. The manual response was affected by whether it was made alone or combined with the vocal response, $F(1, 11) = 13.4$, $p < .01$. Position compatibility, however, did not interact with this variable, $F(1, 11) < 1$ (the effect of position compatibility was 37 ms and 30 ms in the single- and dual-task trials, respectively). The word manipulation had a 16-ms effect on the manual response; this effect was not quite significant, $F(1, 11) = 2.7$, $.1 < p < .15$. When combined with the vocal response, on the other hand, the word manipulation had a 62-ms effect on the manual response. The effect of word compatibility on manual RT when pooled over single- and dual-task trials was significant, $F(1, 11) = 21$, $p < .001$, as was the interaction with the single- versus dual-task variable, $F(1, 11) = 7$, $p < .05$.

Vocal-response data. The vocal response, as expected from the previous experiment, was not affected by the position manipulation when the response was performed alone, but it was greatly affected when combined with the manual response. In contrast, the word manipulation had an effect independent of whether the vocal response was made alone or combined with the manual response. As in the previous experiment, the vocal response was slowed in the dual-task condition, $F(1, 11) = 6$, $p < .05$. The position manipulation did not affect the vocal response by itself, $F(1, 11) < 1$, but when combined with the manual response an effect of 25 ms occurred, $F(1, 11)= 17$, $p < .01$. The word manipulation, on the other hand, had a significant effect on vocal RT, $F(1, 11) = 40$, $p < .001$, but it did not interact with whether the response was made with the manual response or alone, $F(1, 11) < 1$ (there were 71- and 62-ms effects in the single- and dual-task conditions, respectively).

Dual-response data. The dual-response data for the position compatibility manipulation completely replicates the finding for the previous experiment. When combined with the manual response, the vocal response was significantly affected by the position manipulation. Moreover, the 26- and 30-ms effects of the position variable on the vocal and manual RTs, respectively, closely parallel the 25- and 33-ms effects found in Experiment 5. Unlike in Experiment 5, however, position compatibility did not significantly interact with response type, $F(1, 11) = 1.6$, $.2 < p < .25$. Perhaps 12 subjects did not provide the power to pick up a true underlying interaction.

As in the position manipulation, on dual trials the word manipulation had an effect on both manual and vocal responses. Moreover, the word manipulation had a 62-ms effect for both dual manual and dual vocal responses, and thus it did not interact with whether the response was manual or vocal ($F < 1$).

Discussion

The results of the present experiment confirm and extend the conclusions of Experiment 5. When made alone, the vocal task was not significantly affected by the position manipulation, and the manual task was unaffected by the word manipulation. When the responses were combined, however, the position manipulation propagated onto the vocal response as in Experiment 5, and the word manipulation propagated onto the manual response. These results are predicted by either the synchronized-parallel-selection model or the conjoint-selection model.

The critical result of the present experiment, however, is the absence of any sign of underadditivity of the two manipulations. If synchronized parallel selections occurred, then the compatibility manipulations should have been substantially underadditive. Under the synchronized-parallel-selection model, if one selection took much more time than the other, the effect of a variable on processing time for the faster of the two selections would not affect the overall RT. When the word is incongruent with the color, the vocal selection probably takes much longer than selection of the manual response. So in this case, the effect of the position manipulation should be much reduced. On the other hand, when the word is congruent, manual selection will probably be more time-consuming than vocal-response selection. So here the position manipulation will have a large effect. Thus, synchronized parallel selections are ruled out by the additivity of the Simon and Stroop effects. Hence, we conclude that when redundant responses are selected, only a single (conjoint) selection is made, and the response that is selected is a conjunction of two actions (as shown in Figure 8d).

Experiment 7

Experiment 7 checks the assumption made in Experiment 6 that the Stroop manipulation affects the bottleneck stage. A conventional dual-task design is used. Subjects make a button-press response to a tone and then name the color of a word that is presented either 50 ms before the tone or 50, 150, or 450 ms after the tone. When the color is incongruent with the word, and the SOA is long, the response to the word should be about 100 ms longer than when the color is congruent with the word. If the Stroop manipulation affects stages before the bottleneck, however, then when SOA is short—and postponement occurs—the effect should be much smaller (e.g., Pashler, 1984). This follows because at short SO As the bottleneck stage of the second task often must wait for first-task response selection anyway (see Figure 1). On the other hand, if the manipulation affects the bottleneck stage, then the size of the effect should be independent of SOA. (Note that the present experiment does not distinguish between effects on the bottleneck stage itself and stages of processing subsequent to the bottleneck.)

Method

Subjects. Twelve undergraduates at the University of California, San Diego, participated. Nine participated in partial fulfillment of a course requirement, and the remaining 3 were chosen from a pool of paid subjects who participated in several experiments for 4 hr for $20 or $25.

Apparatus and stimuli. The apparatus for the present experiment was identical to that used in the previous experiments. The first stimulus was a tone presented for 300 ms, with a low or high pitch (300 or 800 Hz, respectively). The second stimulus was one of the words "RED," "BLUE," or "GREEN," presented in any of the colors red, blue, or green. The words were 1.9 cm x 2.2, 3.0, and 3.8 cm for the words RED, BLUE, and GREEN, respectively.

Design. The experiment consisted of 1 practice and 14 experimental blocks of 48 trials. Four SOAs (-50, 50, 150, and 450 ms) separated the onset of the first stimulus (the tone) from the second stimulus (the colored word). The word was either compatible with the color (the color named by the word was the same as the color of the word) or incompatible (the word was chosen randomly from one of the two words that were not compatible). The color of the word (red, blue, or green) and the frequency of the tone (high or low) also varied within each block. Each combination of SOA x Compatibility x Color x Frequency occurred once in every block.

Procedure. Each trial was initiated with the presentation of a white plus sign for 1,000 ms in the center of the screen as a fixation point. Two hundred fifty milliseconds after the offset of the fixation point, either the high or low tone was sounded. After the SOA, the colored word was presented at fixation. (For the negative SOA, the word was presented first; the tone, however, was still presented 250 ms after the offset of the fixation point.)

Subjects made two responses. The subject pressed a key labeled *HI* if the tone was a high tone and *LO* if it was a low tone. Second, the subject spoke the name of the color of the word into the microphone. Subjects were told that this second response would be difficult but that they should try to make the response quickly yet accurately. The subjects' vocal responses were recorded, and the subjects were informed of this. Each subject received written instructions. The instructions emphasized making the first response immediately. If during the practice block the subject did not seem to be heeding this, the experimenter badgered the subject until he or she complied.

Results

Figure 12 shows mean RT1 and RT2 as a function of SOA and whether the color of S2 was congruent or incongruent with the word (for trials in which both responses were correct). For each SOA and Stroop combination, we recorded 1,008 trials (12 subjects x 14 blocks x 6 trials per block). Trials in which R1 was faster than 150 ms or slower than 1,500 ms or R2 was faster than 150 ms or slower than 2,500 ms were not included in the analysis.

Subjects' performance on the first task remained stable across all experimental variables. The effect of SOA on RT1 was not significant, $F(3, 33) < 1$, nor was the effect of Stroop, $F(1, 11) = 1.2$, $p > .2$. The interaction of Stroop and SOA

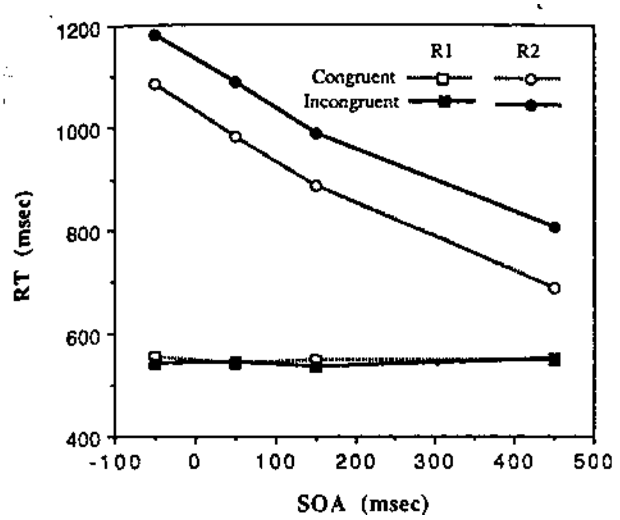

Figure 12. Experiment 7: Mean first- and second-task reaction times (RT1, tone task, and RT2, Stroop task) as a function of stimulus onset asynchrony (SOA) and whether the color of S2 is congruent with the name of S2.

was also not significant, $F(3, 33) = 1.6$, $p > .2$. The error rates on the first task were 4.5%, 3.6%, 2.4%, and 2.5% for SOAs of-50, 50, 150, and 450 ms, respectively. The effect of SOA was significant, $F(3, 33) = 6$, $p < .01$. Neither the effect of the Stroop manipulation on the error rates nor the SOA x Stroop interaction were significant, $F(1, 11) = 2.1$, $p > .15$, and $F < 1$, respectively.

As expected, we found large effects of SOA and Stroop on RT2. The effect of SOA was significant, $F(3, 33) = 340$, $p < .001$, as was the effect of the Stroop manipulation, $F(1, 11) = 68$, $p < .001$. Stroop and SOA did not interact ($F < 1$). The error rates on the second task (the Stroop task) were 7.1%, 6.6%, 5.7%, and 6.9% for SOAs of -50, 50, 150, and 450 ms, respectively. The effect of SOA was not significant, $F(3, 33) = 1.2$, $p > .3$. The Stroop manipulation had a significant effect on the error rates (10.8% vs. 2.3%), $F(1, 11) = 21$, $p < .001$. The Stroop x SOA interaction just missed significance, $F(3, 33) = 2.8$, $.05 < p < .06$.

Discussion

The results were similar to data from a typical dual-task experiment. Whereas SOA had little effect on RT1, RT2 increased dramatically at the shorter SOAs (the PRP effect). Between SOAs of 150 and -50 ms, RT2 increased by 195 ms (a -0.98 slope). Moreover, SOA and the Stroop manipulation had no effect on RT1. But the most important result of this experiment is the lack of interaction between SOA and the Stroop manipulation on RT2. If the Stroop manipulation affected stages prior to the bottleneck, its effect should have been diminished at the short SOAs (see the introduction to this experiment). In fact, because we found nearly a -1 slope over a 200-ms interval of SOA (from -50 to 150 ms), the effect of the Stroop manipulation should have been almost completely washed out at -50-ms SOA. It was not: The 95% confidence interval for the Stroop effect at this SOA ranged from 62.4 to 129.5 ms. Hence it is clear that the Stroop manipulation must affect the bottleneck stage (or some subsequent stage).

Experiments 6 and 7 provide an interesting comparison of the dual-task method of analyzing cognitive processes and the additive factors method (Sternberg, 1969). By additive factors logic, the position and word manipulations affect different stages of processing because they are additive. On the other hand, both manipulations seem to affect the bottleneck mechanism. One resolution of these seemingly conflicting findings is that the two manipulations both effect the same stage, and they are additive only by coincidence. (Additive factors logic does not deny that factors affecting the same stages could add, but it points out that it is coincidental when they do.) A more appealing reconciliation is possible once one recognizes that the two methods decompose processing in different ways. Whereas the additive factors method is aimed at discovering stages, the dual-task method is aimed at discovering mechanisms. Analyzed this way, it is not surprising that the two manipulations add because a single mechanism can certainly be responsible for executing two stages. One could speculate that the Stroop manipulation affects a conceptual decision stage (cf. Seymour, 1977) whereas the Simon manipulation affects a later response programming stage and that the bottleneck mechanism is responsible for performing both of these processing tasks. In fact, the stage that classical additive factors logic has identified as response selection (Sternberg, 1969) may be only one portion of the bottleneck. (For convenience, in this article we have used the term *response selection* as a synonym for the bottleneck stage, but we do not mean this to close the issue).

General Discussion

The seven experiments of this article lead to two major conclusions. First, Experiments 1-3 provide strong evidence that when two responses are made to different attributes of the same object, the response-selection mechanism can select only one response at a time. Though Experiment 1 did not decisively rule out capacity sharing between the response-selection stages of the two tasks, Experiment 2 did provide strong evidence against such a possibility. Furthermore, Experiment 2 produced no evidence that bottleneck processing is any different when both responses are made to one object rather than to two different objects. In Experiment 3 we used a different set of elementary attributes, the color and direction of movement of an object, and again found clear-cut interference between the two tasks. These experiments make it clear that presenting the stimuli as part of the same object is not sufficient to avoid dual-task interference. So the theory that dual-task interference arises because the critical mechanism can initiate processing of information from only one object at a time is ruled out.

Our second major conclusion is that when subjects are required to make two responses to the same aspect of a stimulus (e.g., making a button press to the color of an object and saying the color), they can do this with only a single response selection. In Experiment 4, subjects showed no slowing of the manual response when it was made with a redundant vocal response, and the vocal response was slowed by only 23 ms (effectively ruling out serial selections; see Figure 8a). In Experiment 5, the Simon manipulation, which did not affect single-task vocal responses, affected vocal RT in the dual-task condition. The propagation of the manipulation onto vocal RT in the dual-task condition combined with the high correlations between manual and vocal RT found in these experiments refutes the independent-selection model (Figure 8b).

A synchronized-parallel-selection model (Figure 8c) is consistent with a general propagation of the Simon manipulation onto vocal RT. But a more detailed examination of the effects of this manipulation makes the synchronized-parallel-selection model very unlikely. Assume that the synchronized-parallel-selection model was correct. On many trials in the dual condition, execution of responses would be waiting for completion of manual- rather than vocal-response selection. So the effect of the manipulation on the vocal task under this model should have been much larger in the single-task compared with the dual-task condition. No such interaction occurred, however.

Even stronger evidence against the synchronized-parallel-selection model came from Experiment 6. In this experiment we incorporated both the Simon and Stroop manipulations. When performed alone, the Simon manipulation affected only manual RT, and the Stroop manipulation affected only vocal RT. In the dual-task condition, however, these manipulations each affected manual and vocal RT, and the effects were additive. The conjoint-selection model (Figure 8d) predicts this entire pattern of results. The synchronized-parallel-selection model clearly predicts that these effects should be highly underadditive, and it is therefore ruled out.

Experiment 6 relies on the assumption that both the Stroop and Simon manipulations affect bottleneck stages of processing. Experiment 7 confirmed that the Stroop manipulation does have its effect during the bottleneck. And there is no reason to suppose that this is any different for the Simon manipulation. Moreover, the propagation of the Stroop and Simon manipulations onto the manual and vocal RT, respectively, in the dual-task condition in Experiments 5 (Simon) and 6 (Stroop and Simon) shows that they both have their effects before the processing for the two responses diverges. But it might have been the case, for example, that the Stroop manipulation affected the bottleneck stage and the Simon affected some later stage closer to the response. Then, perhaps parallel response selections are made, and when both are finished the responses are prepared in parallel. This account is consistent with the additivity of the Stroop and Simon effects and the propagation effects found in the dual-task condition. But even this extreme attempt to salvage synchronized parallel response selections does not fit the data. It predicts that the effects of both the Simon manipulation on manual RT and the Stroop manipulation on vocal RT should be significantly less in the dual-task compared with the single-task condition (see Footnote 9), which they are not. Thus it does not seem that this or any other variant of synchronized selections can account for the data.

We therefore conclude that when subjects make two responses to the same attribute of an object, only one response-selection operation need occur. The conjunction of two quite distinct sorts of actions can be selected as if it were a single response. An immediate implication of this conclusion is that the simple action model of the bottleneck is incorrect. The action of the bottleneck mechanism is not limited to selecting one simple motor action at a time. Seemingly arbitrary assemblages of behavior can be selected with but one invocation of this mechanism. Further research is needed to determine if there are exceptions to this, but vocal and manual responses are sufficiently different to warrant the speculation that there will not be.

A Preliminary Model

In this and the following sections, we attempt to explain why a response-selection bottleneck might occur. Other investigators have considered models of response selection in regard to (among other things) skill acquisition (Brown & Carr, 1989) and stimulus-response compatibility (Kornblum, Hasbroucq, & Osman, 1990). The points made by these models could probably still be made within the framework we present.

The most straightforward model of the bottleneck would have the following four properties. (a) Before the task is performed, one or more response-selection rules are activated. The more rules activated, the lower the level of activation that can be reached. (b) Each rule has a condition (the output of the perceptual system) and an action (an abstract motor program). When the condition of a rule is met, the rule fires; the higher the level of activation of the rule, the faster the output becomes available. (c) While one rule fires, another cannot fire. (d) A rule can specify multiple motor responses in its action statement. This framework borrows heavily from what computer scientists term *production systems* (Newell, 1973; for an earlier application of production systems to response selection by humans, see Logan, 1980).

Various findings in the literature are predicted by this model. First of all, dual-task interference and its locus in response selection follow naturally. The fact that preparation will contribute some portion of slowing in dual-task experiments (and the fact that RT2 rarely reaches the speed of Task 2 alone responses, even at very long SOAs) is predicted by this model. The present finding that two actions can be performed with only one response selection when they are redundantly specified follows directly from (d). The postulated role for preparation (a and b) accounts for the slowing of RT1, compared with single-task controls. Further afield, the effect of Hick's law (Hick, 1952), that RT increases linearly with the logarithm of the number of response alternatives, is also compatible with this model. These suggestions are very congenial to Gottsdanker's interesting analysis of the role of preparation (Gottsdanker, 1980), although they are not in keeping with his suggestion that dual-task interference itself might be due solely to preparation problems (Gottsdanker, 1980).

Response-Selection Machinery

The model described previously offers a functional account of the processes (and their timing) that may be responsible for the bottleneck. But it would certainly be useful to have some further description of the machinery that implements these processes. The simplest assumption would be that there is some neural machinery that receives as input the critical stimulus information from perceptual areas and proceeds to retrieve from memory a code for the corresponding action. We can think of this code as a specification of where to find a description of how to produce the response (which, we now know, can actually involve multiple motor actions). The bottleneck is in generating this code: When this retrieval mechanism is busy retrieving one response, the process of retrieval cannot begin for another response. Subsequent mechanisms that look up the response specifications and turn them into action are obviously not limited in the same way. In this account, preparing to perform a speeded-choice task (whether single- or dual-task) corresponds to installing and activating a set of response-selection rules and storing the response specifications to which the output of each response-selection rule points. One recent result that is congenial to this view is reported by Carrier and Pashler (1992): Performing a continuous serial auditory-manual choice-RT task interfered with subjects' ability to carry out various difficult episodic and semantic memory retrievals, despite the enormous differences between the RT task and the memory retrieval.

There is more to be said about the nature of the action code that is retrieved from memory. One obvious possibility is that the code is a motor program: ready—upon selection—to be executed. But the action code that is selected might typically be less complete than this. For example, when naming a letter, the letter being named might not be specified by the action code. Instead, the action code might consist only of an instruction to pronounce whatever letter occupies some buffer set by earlier (perceptual) processes. Note that it follows from this that a letter-naming response would require only one response-selection rule to be activated. This is consistent with (but not proven by) the finding that RT for letter naming does not substantially increase as the number of possible stimulus alternatives increases (Brainard, Irby, Fitts, & Alluisi, 1962).

In short, all of the available evidence is consistent with the bottleneck limitation lying on the machinery responsible for retrieval and generation of action codes. Obviously, that this is the case has not been firmly established, and if it is the case, many questions concerning the nature of the mechanism and the action code remain to be answered.

Complications for the Model

Before accepting this sort of formulation, a major complication must be faced: Evidence suggesting that under certain circumstances simultaneous activation of two responses can take place. There are two relevant sorts of cases. One is response competition, in which flanking stimuli associated with a response other than the correct response slow down the correct response (e.g., B. A. Eriksen & Eriksen, 1974). The usual interpretation is that the flanking stimulus has activated a competing response, slowing down the correct one. The second case is coactivation, in which two stimuli redundantly activate the same response. Miller (1982) argued that the activation of the correct response from two sources proceeds simultaneously. Interestingly, the same pattern of effects (bottleneck but also coactivation) may not be peculiar to speeded-choice tasks but may apply to memory retrieval on a much greater time scale. Carrier and Pashler (1992) found evidence that subjects could not make progress on two cued semantic memory retrievals (e.g., CLOTHING O → overcoat) simultaneously. In activities like solving crossword puzzles, however, people seem to routinely use multiple cues simultaneously to home in on a target to be retrieved (see Nickerson, 1974, for an interesting discussion). If this is correct, it precisely parallels the situation with choice-RT tasks.

These coactivation and response competition effects would seem to directly challenge the sort of production-system model discussed earlier. Why should it be that two stimuli cannot simultaneously activate two different responses, yet two stimuli apparently can simultaneously activate the same response, and a competing stimulus can slow down the process of settling on the correct response (generally presumed to be because it activates a competing response)? There are various possible directions one might explore in attempting to reconcile these conclusions. Perhaps this apparent paradox rests on a faulty interpretation of one or more sets of data. A more interesting reconciliation of these effects would be possible if they resulted from the neural implementation of the look-up process depicted in the production system model sketched before. Suppose that firing of a response rule amounted to a particular set of neurons settling into a particular pattern of activity and that firing of a different response rule amounted to settling into a different pattern of activity in the same set of neurons. In this case, the system would be incapable of firing two different rules at the same time simply because the same neurons could not settle into two different states at the same time. It seems very likely (although it might be worth demonstrating, to be certain), however, that in such networks, two redundant inputs could reinforce each other and speed up the process of settling into one pattern (coactivation), whereas a stimulus associated with a competing response might slow down the settling process (thus producing the Eriksen effect).

The suggestion, then, is that a distributed output representation for response selection might possibly be the key to understanding why response selection constitutes a processing bottleneck, yet at the same time the coactivation and Eriksen effects suggest that more than one stimulus at a time can affect behavior in a way that depends on what responses with which these stimuli are associated. The results of the present article make it clear that if this is correct, the distributed output of response selection cannot be a distributed representation of a motor program, with different patterns of the same units representing different actions (saying a word, pressing a key). After all, subjects can select a vocal and a manual response simultaneously, so long as one stimulus is the basis for selecting both, but two stimuli that independently activate a manual and a vocal responses are subject to queuing (as in the first three experiments of this article). Therefore, although the notion of a distributed output can explain the paradox just posed, we still need to suppose that the distributed output representation represents not a motor program but something more abstract. One might think of it as the index for where to obtain the motor program in some form of "motor working memory." The present results show that the machinery for motor programming and control is perfectly capable of taking such an output and simultaneously producing two appropriate but different sets of muscular patterns.

The theoretical notions explored here are tentative, and further research is obviously needed. Two points are clear, however, about the fundamental limitations on the machinery for selecting and producing actions. The first is that given the enormous amount of parallel processing going on in the human brain at the level of individual neurons and action potentials, people show very profound and stubborn limitations in what are (formally or computationally speaking) very trivial action-selection problems. The second conclusion is that the pattern of these limitations does not correspond to what one would expect from the most straightforward sorts of information-processing mechanisms (such as the production-systems framework). These limitations seem to confound metaphors inspired by phenomena like digital computers, information retrieval in libraries, or allocation of economic resources. This suggests that a deeper understanding of these limitations may be elusive, but it also suggests the problem will be much more interesting than it might have looked at the outset.

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Sales Appointed Editor of New APA Journal, *Psychology, Public Policy, and Law*

In 1994, APA will begin publishing a new journal, *Psychology, Public Policy, and Law.* Bruce Sales, JD, PhD, has been appointed as editor. Starting immediately, manuscripts should be submitted to

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(1) critically evaluate the contributions and potential contributions of psychology and related disciplines to public policy and legal issues (e.g., linking knowledge on risk assessment to global climate change and energy policy; analyzing the fit between FDA policies on food labeling and research on comprehension);

(2) assess the desirability of different public policy alternatives in light of the scientific knowledge base in psychology and related disciplines (e.g., family leave policies considered against a background of knowledge about socialization in dual-career families; retirement policies in light of health, life cycle, and aging);

(3) articulate research needs that address public policy and legal issues for which there is currently insufficient theoretical and empirical knowledge or publish the results of large-scale empirical work addressed to such concerns; and

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