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Locus of the Single-Channel Bottleneck in Dual-Task Interference

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Two experiments used the locus-of-cognitive-slack method to determine whether dual-task interference occurs before or after the response selection stage. The experiments used the overlapping tasks paradigm, in which two signals, each requiring a different speeded choice response, are presented in rapid succession. In Experiment 1, stimulus–response (S-R) compatibility was manipulated by varying whether Task 2 stimuli were mapped onto their responses by a rule or arbitrarily. Compatibility effects were additive with the effects of degree of task overlap, manipulated by varying the stimulus onset asynchrony between the signals. Experiment 2 examined 2 additional forms of S-R compatibility: symbolic compatibility (arrows vs. letters) and spatial compatibility (the "Simon" effect). Effects of symbolic compatibility were additive with effects of degree of task overlap, whereas the effects of spatial compatibility and degree of task overlap were underadditive. It is argued that only a central-bottleneck model provides a consistent account of these results. The nature of the central bottleneck is considered.

People are severely limited in their ability to perform two or more tasks at the same time (Pashler & Johnston, 1989; Vince, 1948; Welford, 1952). The study of this kind of performance limit is important both theoretically and practically. At a theoretical level, understanding multitask interference provides clues to cognitive architecture and the control of mental processes (Keele, 1973). At a practical level, interference between tasks severely limits the functioning of operators in multitask environments such as air traffic control towers. A better understanding of multitask limitations could help improve the performance of such operators.

Two broad classes of models have been advanced to explain interference between tasks. One class (Broadbent, 1971; Pashler & Johnston, 1989; Welford, 1952) holds that interference arises because certain cognitive operations of each task demand simultaneous access to a processor (or processors) that can only service one task at a time. During the time that one task is occupying the bottleneck process(es), there is *postponement* of processing on the other task.

The other major class consists of capacity models (Kahneman, 1973; Navon & Gopher, 1979; Norman & Bobrow, 1975; Wickens, 1980). These models assume that processing relies on graded resources—that is, resources that can be used in differing quantities, with greater quantities producing more efficient or faster processing. These models further assume that graded resources can be divided into separate pools, so that processing on two tasks can proceed simultaneously. Because fewer resources are available to each task under these conditions, the tasks proceed at a reduced rate. Thus, capacity models assume that all stages of processing in each task can proceed simultaneously (but at reduced rates), whereas postponement models assume that some processes in each task are handled strictly serially.

Empirically, it has not been easy to distinguish these classes of models. Part of the problem is the popularity of continuous tasks, such as tracking or shadowing, which measure accuracy over extended time periods (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Wickens, Sandry, & Vidulich, 1983). A number of these studies (e.g., Allport, Antonis, & Reynolds, 1972; Shaffer, 1975) have shown that people can carry out some continuous tasks over the same time periods with only minor impairments of accuracy. Despite claims to the contrary (Allport et al., 1972), these results are not sufficient to reject postponement models. It is plausible that subjects are able to store both perceptual and response codes for short periods of time. With the aid of such information buffers, a single-channel processor could, in principle, switch back and forth between tasks and still maintain a high level of performance on both. More definitive empirical tests require (a) a paradigm in which both stimuli and responses can be precisely measured in time and (b) that responses be traceable to particular stimuli (cf. Broadbent, 1982).

The Overlapping Tasks Paradigm

One such paradigm is the classic overlapping tasks preparation (Welford, 1952, 1959). The subject is presented with two stimuli, S1 and S2, in rapid succession and makes a speeded response to each (R1 and R2, respectively). As the stimulus onset asynchrony (SOA) between S1 and S2 is reduced, processing on the two tasks overlaps more in time, and R2 slows down. The slowing is typically quite dramatic, on the order of several hundred milliseconds.

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A number of accounts of R2 slowing have been proposed. According to postponement theory (e.g., M. C. Smith, 1969; Welford, 1952), certain processes required to perform even relatively easy choice reaction time (RT) tasks constitute a single-channel bottleneck. Only one task can gain access to these processes at any time. While Task 1 is occupying the bottleneck processes, any stage of Task 2 that requires the bottleneck processes must be postponed; such postponement is the cause of R2 slowing.

Postponement theorists disagree on the issue of where the bottleneck is located. Some (e.g., Pashler, 1984; Pashler & Johnston, 1989; M. C. Smith, 1969; Welford, 1952) argue that the bottleneck occurs at or before the level of central processes associated with decision making, response selection, or both. Others (e.g., Keele, 1973; Keele & Neill, 1978; Logan & Burkell, 1986; Norman & Shallice, 1986) claim that there is no bottleneck prior to actual initiation/execution of responses. In their view, response selection on Task 2 occurs in parallel with processing on Task 1, and only the actual execution of the response is subject to postponement.

Capacity theorists (e.g., Kahneman, 1973; McCleod, 1977) offer another account of R2 slowing. Both tasks are assumed to draw on a central pool of attentional capacity. At long SOAs, Task 1 is completed before Task 2 begins, so that each task has access to the entire pool. At short SOAs, however, the demands of the two tasks overlap. The capacity allocated to Task 2 is reduced under these conditions, the rate of processing on Task 2 slows down, and the response time to Task 2 (RT2) increases.

Two issues await resolution. First, we want to determine whether R2 slowing is due to capacity sharing or postponement. Second, if R2 slowing is due to postponement, we want to determine where in the sequence of processing stages the bottleneck occurs.

The Locus-of-Slack Approach

Recent work on the organization of mental processes provides a powerful chronometric method with which to examine these issues (Pashler, 1984; Pashler & Johnston, 1989; Schweickert, 1978, 1980). To illustrate the method, which we call the *locus-of-slack* approach, Figure 1 shows a timing diagram for two two-choice RT tasks. Suppose (cf. Sternberg, 1969) each task can be decomposed into three sequential processing stages: 1A, 1B, and 1C for Task 1 and 2A, 2B, and 2C for Task 2. Suppose further that the central stage constitutes a single-channel bottleneck; the same processors are required for Stages 1B and 2B, and they can service only one task at a time. Assuming that Stage 1B has priority, these processors will not be available to Stage 2B until they have completed Stage 1B. This produces a period of "cognitive slack" (Schweickert, 1978, 1980, 1983), represented by the gap between the boxes for Stage 2A and 2B in the bottom panel of Figure 1, during which no further processing on Task 2 occurs. By contrast, Stages 2A and 2C do not require the services of any processors required on Task 1. Thus, Stage 2A can proceed during slack.[1]

Empirically, the locus-of-slack approach requires manipulating both task overlap (SOA) and another factor influencing Task 2 difficulty. In Figure 1, the factor influences the duration of Stage 2B. The diagram shows that cognitive slack is absent at long SOAs (top panel) and present at short SOAs (bottom panel). But because Stage 2B occurs after the slack, in both cases a k-ms increase in Stage 2B duration shows up as a k-ms increase in RT2. As a result, there is additivity of the task overlap factor and the Task 2 difficulty factor.

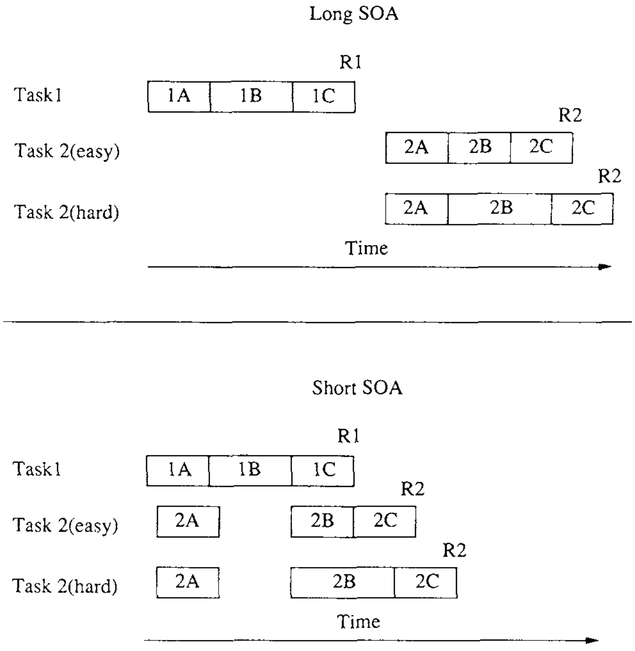

Figure 1. Top panel: Stage analysis of Task 1 and Task 2 processing at a relatively long stimulus onset asynchrony (SOA). (Task 2 is shown under two levels of a factor that selectively influences the length of Stage 2B; the short Stage 2B corresponds to Task 2 [easy], and the long Stage 2B corresponds to Task 2 [hard].) Bottom panel: A similar analysis of Task 1 and Task 2 processing at a relatively short SOA. (Note the presence of cognitive slack in the form of the gap between Stages 2A and 2B. Because 2B occurs after the slack period, factor effects are fully reflected in a slowing of R2.)

Figure 2 shows a factor that affects Stage 2A duration. At long SOAs (top panel), factor-induced lengthening of Stage 2A lengthens RT2 by the same amount. At intermediate SOAs (not shown in the figure), slack emerges but is not long enough to absorb all of the factor effect; some is passed on to RT2 (Pashler & Johnston, 1989). The bottom panel shows an SOA value so short that all of the factor-induced lengthening of Stage 2A is absorbed in slack, and the factor no longer affects RT2. The net result is that factor effects shrink as SOA is reduced until, at very short SOAs, the effect is eliminated entirely.[2]

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[1] The appropriateness of these assumptions, of course, depends on the detailed requirements of each task. For instance, the assumption that Stages 1A and 2A can run simultaneously may be false if the perceptual processing required of the two tasks is highly similar.

[2] So far, to simplify exposition, we have assumed deterministic (fixed) stage durations. Clearly it is more realistic to assume that stage durations in both Task 1 and Task 2 are subject to considerable trial-

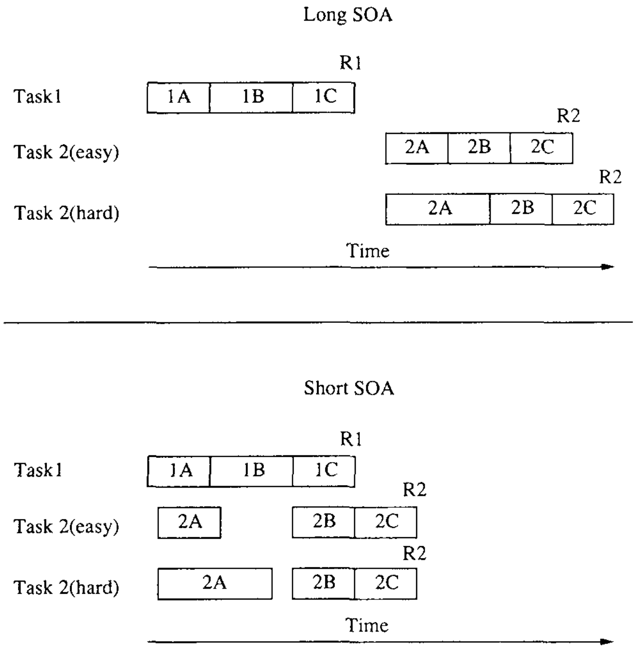

Figure 2. Top panel: Stage analysis of Task 1 and Task 2 processing at a relatively long stimulus onset asynchrony (SOA). (Task 2 is shown under two levels of a factor that selectively influences the length of Stage 2A; the short Stage 2A corresponds to Task 2 [easy], and the long Stage 2A corresponds to Task 2 [hard].) Bottom panel: A similar analysis of Task 1 and Task 2 processing at a relatively short SOA. (Here the slack interval absorbs the difference between Stage 2A [short] and Stage 2A [long], so that factor-related slowing of Stage 2A does not affect R2.)

To summarize, the locus-of-slack technique provides an empirical method to distinguish stages of processing that lie at or beyond the bottleneck from stages located prior to the bottleneck. If a factor influences the duration of a stage at or beyond the bottleneck, factor effects will be *additive* with effects of SOA. If a factor influences the duration of a stage prior to the bottleneck, factor effects will be *underadditive* with effects of SOA.

The Locus-of-Slack Technique and Capacity Models

How do these predictions compare to predictions from capacity-sharing models? For these models, increasing task difficulty corresponds to increasing the quantity of work to be done. It is easy to show that the same fixed increase in work produces a larger increase in task duration if the resources available to do the work are simultaneously reduced (e.g., under dual-task conditions). By this reasoning, McCleod (1977) concluded that increases in task difficulty should have a larger effect on response time when capacity is reduced by dual-task interference. Capacity theory therefore predicts *overadditive* interactions between Task 2 difficulty factors and task overlap (SOA).

Thus, the locus-of-slack technique is particularly valuable for distinguishing postponement models from capacity-sharing models. According to postponement models, effects of Task 2 difficulty should be either additive or underadditive with effects of SOA, depending on the stage whose duration is increased. On the other hand, the natural prediction of capacity-sharing models is that Task 2 difficulty effects should be overadditive with the effects of SOA (cf. McCleod, 1977).

Previous Evidence

Preliminary tests using the locus-of-slack technique were reported by Pashler (1984) and Pashler and Johnston (1989). In both studies, S2 encoding difficulty was varied by manipulating S2 intensity. Reducing S2 intensity increased RT2, but the size of the effect decreased as SOA decreased (Pashler & Johnston, 1989). Following locus-of-slack logic, the underadditive interaction supports a postponement model of overlapping tasks interference with a bottleneck after the encoding stage. Using a somewhat different methodology, Pashler (1989, 1991) has reported further evidence that early perceptual processing is not subject to dual-task bottlenecks.

If the bottleneck is not in early perceptual processing, where is it? One possibility is that the bottleneck arises in the central stage where identified stimuli are mapped onto responses (Welford, 1952). Alternatively, the bottleneck might not occur until later, at the point where responses are initiated (Keele, 1973). Many researchers have brought evidence to bear on this topic. Unfortunately, most of this evidence is based on the manipulation of variables not clearly associated with one particular stage of processing. Thus, strong evidence for one alternative or the other is still lacking.

For example, Pashler and Johnston (1989) found that the effects of trial-by-trial stimulus repetition were additive with the effects of SOA. Pashler and Johnston cited evidence that repetition effects are located in the response selection stage and concluded that the processing bottleneck lies at or before this stage. However, repetition is inherently ill-suited to a stages analysis. A repeated trial repeats the stimulus, the response, and everything in between. Thus, logically, all stages are candidates for a speedup on repeated trials. Converging evidence is needed.

In a paradigm in which Task 2 consisted of visual search for a target letter among letter distracters, Pashler (1984) found that effects of response type (*yes* faster than *no*) were additive with task overlap effects. Pashler assumed that the effects of stimulus presence–absence are in response selection and concluded that the bottleneck is in response selection. Here again, there is uncertainty about the processing locus of the effect. The physical responses on present and absent trials are different, and it is quite likely that one of the responses (presumably the "present" response) was in a higher overall activation stage than the other. Thus presence versus absence

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by-trial variance. This does not affect the prediction that factor effects in Stage 2B will be additive with the effects of task overlap (SOA). For factors affecting Stage 2A, one must now take into account that both the length of the slack period and the length of Stage 2A are subject to variability. Whenever cognitive slack occurs, some of the effect of lengthening Stage 2A will be absorbed. The entire factor effect will be absorbed only in the extreme case where sufficient slack exists on every trial to absorb the lengthening of Stage 2A that occurs on that trial.

could plausibly affect the very late stage of response initiation/execution. The other end of the processing chain also remains a possibility. Pashler and Badgio (1985) found that presence versus absence interacts with stimulus quality, indicating a much earlier locus than Pashler (1984) assumed.

Schweickert (1978) previously argued for a response selection bottleneck on the basis of a locus-of-slack analysis of data from Greenwald (1972). Unfortunately, Greenwald's tasks involved Stroop-like conflicts in the coding of R1 and R2. These conflicts may have forced sequential processing of response selection, so that Schweickert's conclusion may apply only to a special case.

Other results have been taken as favoring a late-bottleneck model in which response selection is carried out during cognitive slack and only response initiation/execution is subject to postponement. Karlin and Kestenbaum (1968) compared the latency advantage for a simple RT task over a choice RT task when the tasks were performed alone and when they were performed as Task 2 in the overlapping tasks paradigm. Under dual-task conditions, the advantage for simple versus choice RT tasks was reduced; the effects of task type and dual-task interference were underadditive. Keele (1973) argued that the key difference between these tasks is that response selection is more complex for choice RT than simple RT. Using locus-of-slack logic, he argued that the underadditive interaction meant that the response selection stage was being absorbed into slack. He concluded, therefore, that R2 slowing must be due to a later bottleneck, in the response initiation/execution stage.

Keele's argument assumes that simple and choice RT tasks differ only in their response selection requirements. However, there is evidence that part of the advantage for simple over choice RT lies in better preparation in the simple task (cf. E. E. Smith, 1968). If preparation on Task 2 is disrupted at short SOAs (Gottsdanker, 1980), then some of the simple RT advantage would be lost for reasons that have nothing to do with carrying out response selection procedures during slack.

Additional support for a late-bottleneck model was reported by Logan and Burkell (1986). In their study, most trials included only one choice RT task. On some trials, however, the signal for the choice task was followed by a second signal. Subjects were instructed to try to respond to this second signal while canceling their response to the first signal. On trials where they failed to inhibit this response (R1 in our terminology), responses to the second signal (R2) showed the standard increase in latency as the SOA between the two signals was reduced. When R1 was successfully withheld, however, RT2 became flat against SOA; overlapping tasks interference was abolished. Logan and Burkell argued that withholding R1 differed from making R1 only in the absence of the response execution stage, and they therefore concluded that response execution is the source of the bottleneck. But this conclusion assumes that on trials where R1 was not executed, subjects nevertheless completed the response selection process on Task 1. Logan and Burkell offered no evidence against the hypothesis that response selection on Task 1 was *interrupted by the second signal* before proceeding to completion, so their conclusion is not compelling.

The Present Experiments

Decisive evidence in favor of either the central-bottleneck postponement model or the late-bottleneck postponement model of overlapping tasks interference is lacking. The key issue is whether the bottleneck occurs before or after response selection, the stage at which identified stimuli are mapped onto response categories. More conclusive evidence requires a variable whose effects are clearly confined to the response selection stage.

The most obvious candidate is stimulus–response compatibility. It is well established that some stimulus–response mapping arrangements are more natural or compatible than others (Fitts & Deininger, 1954; Fitts & Seeger, 1953). A large number of experiments using the additive factors method (Sternberg, 1969) support the commonsense view that stimulus–response (S-R) compatibility effects are confined to the response selection stage (e.g., Alluisi, Strain, & Thurmond, 1964; Frowein & Sanders, 1978; Hasbroucq, Guiard, & Kornblum, 1989; Inhoff, Rosenbaum, Gordon, & Campbell, 1984; Schwartz, Pomerantz, & Egeth, 1977; Shulman & McConkie, 1973; Spijkers & Walter, 1985; Whitaker, 1979). A manipulation of S-R compatibility in the locus-of-slack paradigm should distinguish central-bottleneck models from late-bottleneck models. Additive effects of S-R compatibility and task overlap (SOA) would provide strong evidence that the bottleneck lies at or before response selection. Underadditive effects would indicate that response selection is absorbed into the slack period and hence that the bottleneck occurs at the later stage of response initiation/execution.

A second goal in testing S-R compatibility effects in the overlapping tasks paradigm is to provide a better test of postponement versus capacity-sharing models. As noted earlier, the most straightforward version of capacity theory (McCleod, 1977) predicts overadditive effects of dual-task slowing and any Task 2 difficulty factor. Pashler and Johnston (1989) argued that the underadditive interaction between stimulus intensity and task overlap is therefore strong evidence against capacity-sharing models. However, capacity theorists might argue that very early forms of processing, such as stimulus encoding, are too peripheral to influence the capacity required to perform the task. Thus, capacity theorists can accommodate the failure to find an overadditive interaction of stimulus intensity and task overlap.

This argument is less plausible for manipulations of S-R compatibility, because they affect the difficulty of the S-R translation stage. S-R translation includes relatively complex processing, presumably including decision making and the retrieval of information from memory (Duncan, 1977, 1978; Sternberg, 1969). Thus, any reasonable version of capacity theory should concede that S-R translation is subject to capacity limitations. If we fail to find an overadditive interaction of S-R translation difficulty and task overlap, the case against capacity theory will be strengthened considerably.

Experiment 1

In Experiment 1 we used two-choice RT tasks. The stimuli for Task 1 were two pure tones presented in rapid succession.

Subjects were required to decide whether the frequency of the second (comparison) tone was higher or lower than the frequency of the initial (standard) tone. Task 2 mapped six alternative stimuli onto six alternative responses. Three sizes of triangles and three sizes of circles were mapped onto the three middle fingers of each hand. Shape was the defining feature for hand (e.g., triangles mapped onto the right hand and rectangles mapped onto the left hand), and size was the defining feature for finger.

S-R compatibility was manipulated by varying (between shapes) the availability of a simple rule relating stimulus size to response finger. For one shape there was an ordered relation between the size of the shape and the correct finger: small shape to left finger, medium shape to middle finger, and large shape to right finger. For the other shape, to which responses were made with the other hand, the relation between stimulus size and responding finger was arbitrary.

Response selection should be faster when subjects can use the relation between stimulus size and response finger as an S-R translation rule (Duncan, 1977, 1978; Proctor & Reeve, 1985). The critical question is whether S-R translation difficulty interacts with SOA. According to the postponement model of dual-task interference, with a bottleneck at or before response selection (Pashler & Johnston, 1989), the effect of S-R translation difficulty should be additive with the effects of SOA. On the other hand, if the bottleneck occurs after response selection, response selection effects should get absorbed into slack, producing an underadditive interaction with SOA. If capacity theory rather than postponement theory is correct, an overadditive interaction should be observed.

Method

Subjects. The subjects were 24 right-handed students with normal or corrected-to-normal vision who were recruited from universities and community colleges in the area surrounding the NASA–Ames Research Center. Their ages ranged between 18 and 40 years.

Stimuli and apparatus. Stimuli were presented on an IBM AT microcomputer with a Sigma Design Color-400 graphics board and a Princeton SR-12 (640 × 400 resolution) monitor. Task 1 stimuli were two computer-generated 500-ms tones separated by a 300-ms intertone interval. The first (reference) tone was randomly selected from a range between 500 Hz and 600 Hz. The second (comparison) tone was either 8% higher or 8% lower than the reference tone. Verbal responses were registered by a voice-activated relay from a Shure highly directional microphone (Model 849).

S2 consisted of either a rectangle or a triangle in one of three sizes. From a viewing distance of approximately 75 cm, the three sizes subtended visual angles of 0.73° (diagonal extent = 0.7 cm) for the small shapes, 0.97° (diagonal extent = 1.3 cm) for the medium shapes, and 1.9° (diagonal extent = 2.5 cm) for the large shapes. The shapes, all magenta, appeared in the center of a yellow circle covering 2.7° of visual angle (diameter = 3.5 cm). The circle was present throughout the intertrial interval and during the trial itself, with the exception noted in the *Procedure* section.

Design. The experiment consisted of two sessions. Each session contained 12 blocks of 48 trials each. Within a block, each combination of the following variables was represented by a single trial: Task 1 type (comparison tone higher than reference tone vs. comparison tone lower than reference tone), Task 2 shape (triangle vs. rectangle), shape size (small, medium, or large), and SOA between comparison tone onset and shape onset (50, 150, 300, or 800 ms). Collapsing across Task 1 type and responding finger, each block contained six replications for the two levels of Task 2 difficulty (consistent mapping of size to finger vs. arbitrary mapping of size to finger) by four SOAs. Order of trial presentation was randomized separately for each subject.

To achieve appropriate counterbalancing, eight different mappings of stimuli to responses were used. These mappings included all possible combinations of the following three binary variables: which shape to which hand (e.g., triangle mapped to right hand, rectangle to left hand, or vice versa), which shape to which type of mapping (e.g., triangle to consistent rule and rectangle to arbitrary rule or vice versa), and which variant of arbitrary mapping (e.g., either A: mapping large size to left finger, small size to middle finger, medium size to right finger, or B: mapping medium size to left finger, small size to middle finger, and large size to right finger). Each of the eight resulting mapping arrangements was assigned to 3 subjects.

Procedure. Subjects were given written instructions explaining the events on each trial. Each trial consisted of two tasks. The first task was to verbally respond "high" if the comparison tone was higher than the reference tone and "low" if it was lower. The second task was to respond to the shape as quickly as possible, by depressing one of six keys: Z, X, and C with the ring finger, middle finger, and forefinger, respectively, of the left hand, and the comma key, the period key, and the slash key with the forefinger, middle finger, and ring finger, respectively, of the right hand.

Each trial began when the circle disappeared for 300 ms and then reappeared. A variable foreperiod followed, composed of a base of 500 ms plus a variable number of additional 50-ms increments, with a .33 probability of ending with each additional increment. The reference tone then sounded for 500 ms. After a 300-ms delay, the comparison tone sounded for 500 ms. The shape appeared in the middle of the circle at one of four intervals following the onset of the comparison tone: 50, 150, 300, or 800 ms. The shape remained on the screen until the computer registered both a vocal and a key-press response or 3,000 ms had elapsed. After the trial, subjects scored their own verbal responses by pressing the Y or the N keys on the keyboard in response to a screen query (e.g., "Did you say low?"). The query remained on the screen until the computer recorded a Y or an N response, after which the circle reappeared. The intertrial interval was approximately 1 s.

Careful efforts were made to discourage subjects from adapting a "conjoint responding" strategy (Pashler & Johnston, 1989) in which R1 is withheld until R2 is also selected and then both responses are executed as a unit. Subjects were explicitly instructed to respond to the comparison tone as soon as possible, without waiting for the shape. In addition, after each block they were shown the difference between mean RT1s for the two shorter SOAs (50 ms and 150 ms) and for the two longer SOAs (300 ms and 800 ms). Subjects were told that if the difference was "greater than about 20," they should try harder to respond rapidly to the comparison tone.

Assistance in learning the Task 2 mappings was provided by a diagram illustrating the correct mapping of shape to finger, located just below the computer screen. Subjects were told to use the diagram until they had learned the Task 2 mappings and then to watch the middle of the circle at all times.

Results

Data from the first session were considered practice and are not reported. In addition, the first two blocks of trials on the 2nd day were considered warm-ups and were omitted from the analysis. All trials with an error on either Task 1 or Task

2 were excluded from the RT analysis. Furthermore, we discarded trials with missing responses, or any of the following: RT1s or RT2s less than 150 ms, RT1s greater than 1,500 ms, and RT2s greater than 2,000 ms. These criteria resulted in 224 ineligible trials (1.9% of the total). For each subject and task, trials beyond three standard deviations of the cell mean were also excluded, subject to the constraint that no more than three trials were removed from any cell. Outlier trimming removed 117 additional data points (1% of the total) for Task 1 and 161 trials (1.4% of the total) for Task 2.

Figure 3 shows mean RT1s and mean RT2s as a function of Task 2 difficulty (ordered vs. arbitrary mapping) and SOA between S1 and S2. For each task, these effects were assessed in a 2 (Task 2 difficulty) by 4 (SOA) repeated measures analysis of variance (ANOVA). The effects of SOA on RT1, although small, were statistically significant, $F(3, 69) = 5.5$, $p < .01$. The effect of Task 2 difficulty on RT1, although again small (5 ms), was also significant, $F(1, 23) = 6.11$, $p < .01$. There was no hint of a Task 2 difficulty by SOA interaction, $F(3, 69) < 1$.

Task 2. RT2 was 60 ms faster to consistently mapped shapes than to arbitrarily mapped shapes, $F(1, 23) = 10.9$, $p < .01$. That is, responses were faster when S-R compatibility was greater. RT2 also increased monotonically with reductions in SOA, $F(1, 23) = 72.1$, $p < .001$, the usual RT2 dual-task slowing. Most important, there was no systematic relation between Task 2 difficulty and SOA; compatibility effects were as follows: SOA 50, 55 ms; SOA 150, 66 ms; SOA 300, 49 ms; and SOA 800, 72 ms. The interaction between Task 2 difficulty and SOA did not approach significance, $F(3, 69) = 1.94$, $p > .10$.

Error rates. Reported error rates in Task 1 were too few (< 2%) to warrant analysis. Table 1 shows Task 2 error rates as a function of SOA and S-R compatibility (e.g., Task 2 difficulty). In an overall analysis including compatibility and SOA as factors, only the compatibility effect (subjects made 1.8% fewer errors to the ordered shapes) approached significance, $F(1, 23) = 3.77$, $.10 > p > .05$. As with RTs, there was no hint of an SOA by Task 2 difficulty interaction, $F(3, 69) < 1$.

Discussion

The results of Experiment 1 are hard to reconcile with capacity-sharing models in which dual-task interference reduces the rate of processing. Capacity-sharing models predict that effects of task overlap (i.e., SOA) should produce overadditive interactions with manipulations of Task 2 difficulty, such as S-R compatibility. The results showed no hint of an overadditive interaction.[3]

How do the results bear on the locus of interference? A late-bottleneck model of R2 slowing assumes that response selection activity is performed in parallel on Task 1 and Task 2. If so, S-R compatibility effects should diminish as SOA is reduced and cognitive slack increases. The alternative model assumes a central bottleneck at or before the response selection stage, so the response selection stage should be subject to postponement. According to this model, S-R compatibility effects are located in processes that occur after the slack period. These effects should therefore remain unchanged as SOA is reduced, even though RT2 lengthens.

The results of the experiment clearly favor the central-bottleneck account. S-R compatibility effects did not vary significantly with SOA, and the obtained trends were not systematic; indeed, the mean S-R compatibility effect across the two shorter SOAs was identical to the effect across the two longer SOAs (60 ms). According to locus-of-slack logic, the results indicate that processes of S-R translation are subject to postponement, consistent with a central-bottleneck account of R2 slowing.

The generality of the results in Experiment 1 might be questioned on grounds that the response selection process on Task 2 was quite difficult. Subjects had to learn a total of six S-R mappings; the mappings required analyses of two distinct stimulus attributes, size and shape; and the size analysis required a comparison between the stimulus and an implicit standard that was not physically present and hence had to be fetched from memory. It is possible that response selection is subject to postponement only when it is quite difficult. Do our results favoring a central-bottleneck model generalize to easier S-R mappings?

Experiment 2

In Experiment 2 we further assessed the joint effects of S-R compatibility and overlapping tasks interference in a paradigm where response selection procedures for Task 2 were simplified considerably. Stimuli for Task 2 included arrows pointing to the right or the left (easy condition) and the letters M and T (hard condition). The left arrow and one letter required a left-hand forefinger response, and the right arrow and the remaining letter required a right-hand forefinger response. This design simplified Task 2 from the 6:6 mapping in Experiment 1 to a 4:2 mapping. Also, subjects had to process only one stimulus attribute (identity) rather than two.

The use of arrows and letters manipulated symbolic S-R compatibility (Simon, Sly, & Vilapakkam, 1981), the degree of natural correspondence between stimulus and response at a conceptual or semantic level. Compared to arbitrary letters, arrows have a strong preexisting association with the concepts of left and right. When responses are likely to be coded in terms of left and right, response selection should be faster for arrows than for letters (Arend & Wandmacher, 1987; Proctor & Reeve, 1985).

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[3] Capacity theories also make a number of predictions concerning the effects of task overlap on RT1 that are not supported by the present results. First, capacity theory predicts that RT1 should get progressively slower as the tasks overlap more in time. In fact, RT1 was almost flat across the SOA range, and the residual trend was in the wrong direction; RT1 was highest at the longest SOA, where task overlap is essentially nonexistent. Second, any effect of Task 2 difficulty on R1 should increase as SOA is reduced. Task 2 difficulty in fact had only a modest (5-ms) overall effect on RT1, and this effect was not exacerbated at short SOAs. Pashler and Johnston (1989) provided a detailed account of how residual effects on RT1 can be explained within a postponement theory framework by residual grouping tendencies.

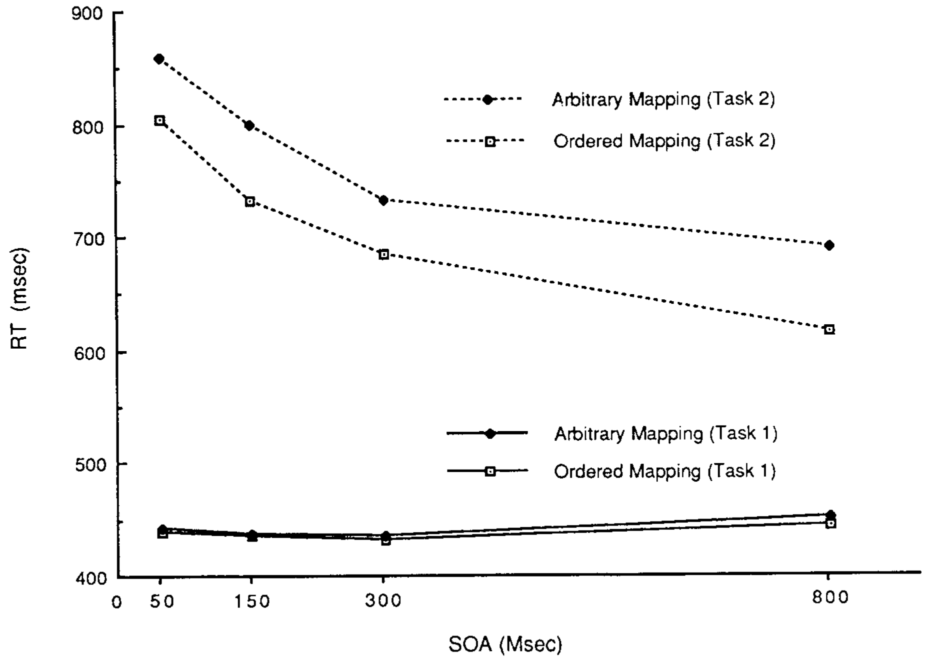

Figure 3. Mean response times (RTs) for Task 1 and Task 2 in Experiment 1 as a function of stimulus onset asynchrony (SOA) and Task 2 difficulty (ordered mapping vs. arbitrary mapping).

The critical test is whether effects of symbolic S-R compatibility (a measure of response selection difficulty) interact with SOA. If R2 slowing is the product of a bottleneck at or before response selection, effects of symbolic compatibility and SOA should be additive, as were effects of response selection difficulty and SOA in Experiment 1. In addition, the manipulation of symbolic compatibility provides a further test of postponement models versus capacity models, because the latter predict overadditivity between symbolic compatibility effects and SOA.

A second purpose of Experiment 2 was to examine the effects of practice. It seems reasonable that practice might further reduce the difficulty of response selection (Proctor & Reeve, 1988; Pashler & Baylis, 1991). Higher practice levels also provide a further test of the generality of the results of Experiment 1.

The Simon Effect

In Experiment 2, S2 appeared either to the left or the right of fixation, so that the position of S2 corresponded to either the position of the correct response or the position of the incorrect (opposite) response. Responses are generally faster when the positions of the stimulus and the response correspond than when they do not correspond (Craft & Simon, 1970). This spatial compatibility effect is known as the Simon effect (after Hedge & Marsh, 1975).

The manipulation of spatial compatibility in addition to symbolic compatibility provides a further opportunity to test the central-bottleneck model against its competitors. For reasons discussed earlier, capacity-sharing models naturally predict that each source of difficulty should interact overadditively with SOA. Late-bottleneck models assume that all processing, excepting only response initiation/execution, is accomplished during cognitive slack. Because there is strong evidence that the Simon effect is located at a stage prior to response initiation/execution (Stoffels, Van der Molen, & Keuss, 1989), late-bottleneck models predict that spatial compatibility and symbolic compatibility will interact underadditively with SOA.

As we noted, the central-bottleneck version of postponement models predicts additivity between the effects of symbolic compatibility and SOA. At the time these experiments were conducted, we had assumed that the Simon effect was located in the response selection stage (Mewaldt, Connelly, & Simon, 1980; Simon et al., 1981; Umilta & Nicoletti, 1985). If that assumption is true, the most straightforward prediction of the central-bottleneck model is that the Simon effect will be additive with SOA.

There are two reasons for skepticism about this prediction, however. The first reason is that the association between the Simon effect and the response selection stage has recently been questioned. Hasbroucq and Guiard (1991) and Stoffels et al. (1989) argued that the Simon effect is associated with

Table 1
Task 2 Error Rates (%) in Experiment 1

Mapping condition	Stimulus onset asynchrony (in milliseconds) 50	150	300	800
Ordered mapping	3.9	5.0	4.7	3.6
Arbitrary mapping	5.4	6.4	6.1	6.2

processes of stimulus identification, rather than with response selection. If stimulus identification does not form a bottleneck, and if Hasbroucq and Guiard and Stoffels et al. are correct, locus-of-slack logic suggests that the Simon effect will be underadditive with SOA.

There is also an alternative other than absorption into slack time that might yield an interaction. Existing evidence (Simon, Acosta, Mewaldt, & Spiedel, 1976) indicates that the Simon effect is short-lived, persisting for only a brief period following stimulus onset. The presence of cognitive slack prior to S2–R2 mapping might provide the time necessary for the effect to dissipate. We will have more to say about this possibility later.

To summarize, each of the three models of R2 slowing in the overlapping tasks paradigm predicts a different set of outcomes for Experiment 2. Capacity-sharing models most naturally predict that effects of both symbolic S-R compatibility and spatial S-R compatibility will be overadditive with effects of SOA. A late-bottleneck version of postponement models, in which only response initiation/execution is subject to postponement, predicts that both difficulty manipulations will be underadditive with SOA. Finally, postponement models with a central bottleneck at or before the stage of response selection predict that symbolic compatibility effects will be additive with SOA. The Simon effect will not interact overadditively with SOA. The effect could interact additively if it occurs during response selection and if temporal contiguity between S2 onset and R2 selection is not critical. Both assumptions are open to question, however, raising the possibility of an underadditive pattern instead.

Method

Except as noted below, the apparatus and procedure were the same as in Experiment 1.

Subjects. The subjects were 20 undergraduates recruited from universities and colleges near the NASA-Ames Research Center. Each subject had normal or corrected-to-normal vision and participated in three sessions lasting approximately 70 min each.

Stimuli. Task 2 stimuli included two arrows, one pointing to the left and one to the right, and the letters M and T. The letters measured 1.4 cm in height and 0.8 cm in width, and the figures for the arrows were approximately reversed. At a standard viewing distance of 75 cm, these stimuli subtended 1.07° of visual angle on the long axis and 0.61° along the short axis. All stimuli were centered 8 cm to the left or 8 cm to the right of a central fixation cross. Thus, they appeared 6.11° to the left or right of fixation.

Design. Each session consisted of eight blocks of 64 trials. Each block contained two replicates for the factorial combination of the following variables: Task 1 type (reference tone higher than comparison tone vs. reference tone lower than comparison tone), symbolic compatibility (arrows vs. letters), spatial compatibility (position of the stimulus and position of the response corresponded vs. positions of the stimulus and response did not correspond), and SOA (50, 150, 300, or 800 ms).

Procedure. Subjects rested the forefingers of each hand on buttons mounted on a response box. The buttons were separated by approximately 17 cm; the response box was positioned such that each button was approximately aligned with the location of the corresponding S2 on the screen. Subjects responded to the left arrow by pressing the button under the left forefinger and to the right arrow by pressing the button under the right forefinger. For half of the subjects the letter M was assigned to the left forefinger response and the letter T to the right forefinger response; for the remaining subjects these assignments were reversed. On half of the trials, S2 occurred on the same side of fixation as the responding finger, whereas on the remaining trials the position of S2 was opposite to the responding finger. Thus spatial S-R compatibility and symbolic S-R compatibility varied orthogonally.

In a further change from Experiment 1, subjects viewed a central fixation cross rather than a circle during the intertrial interval. The offset of the fixation cross served an alerting function for the following trial, and the cross did not reappear until the subject finished classifying his or her response to Task 1.

Results

All three sessions were included in the analysis. Trial acceptance criteria followed those of Experiment 1, except that the RT2 cutoff was reduced from 2,000 to 1,500 ms. Altogether, 693 trials were excluded (3% of the total). Outlier trimming excluded a further 126 trials (< 1% of the total) for Task 1 and 194 trials (< 1% of the total) for Task 2.

Task 1. RT1 was assessed in a 3 (days) by 2 (symbolic compatibility) by 2 (spatial compatibility) by 4 (SOA) repeated measures ANOVA. There were significant main effects of days, $F(2, 38) = 5.89$, $p < .01$; mean RT1 fell from 516 ms on Day 1 to 459 ms on Day 3. The main effect of SOA was also significant, $F(3, 57) = 8.1$, $p < .01$, reflecting a small increase in RT1 as SOA increased (mean RT1s were 477, 480, 486, and 490 ms, respectively, for the 50-, 150-, 300-, and 800-ms SOAs). The pattern suggests a small tendency for subjects to group responses (Pashler & Johnston, 1989) despite our efforts to prevent the strategy. No other effects on RT1 were significant.

Task 2. Overall, RT2 averaged 624 ms (mean error rate = 4.0%), compared with 740 ms (mean error rate = 5.2%) for the second session of Experiment 1. These results confirm that Task 2 was considerably easier than in Experiment 1. RT2 was submitted to the same four-way repeated measures ANOVA described for RT1. The analysis revealed significant main effects of days (RT2 was reduced from 707 ms in the first session to 562 ms in the third), $F(2, 38) = 32.2$, $p < .001$, and SOA (mean RT2s were 524, 594, 656, and 722 ms for the 800-, 300-, 150-, and 50-ms SOAs, respectively), $F(3, 57) = 68$, $p < .001$. Responses to arrows were 59 ms faster than responses to letters, $F(1, 19) = 26.6$, $p < .001$, and spatially corresponding trials were 16 ms faster than spatially noncorresponding trials, $F(1, 19) = 19.8$, $p < .001$.

These results establish reliable main effects of both symbolic and spatial S-R compatibility (i.e., the Simon effect), practice, and task overlap (SOA). For present purposes, the more interesting questions concern various possible interactions. As shown in Figure 4, the symbolic compatibility effect did not vary by more than a few milliseconds across SOA; the interaction did not approach significance, $F(3, 57) < 1$. Furthermore, there was no hint of a three-way interaction between task overlap, symbolic compatibility, and practice, $F(6, 114) < 1$. Thus, dual-task slowing and symbolic compatibility had additive effects on performance, and the additive pattern was robust over practice. Figure 5 presents the joint effects of SOA and spatial compatibility. In contrast to the previous pattern, the Simon effect decreased monotonically across SOA, from

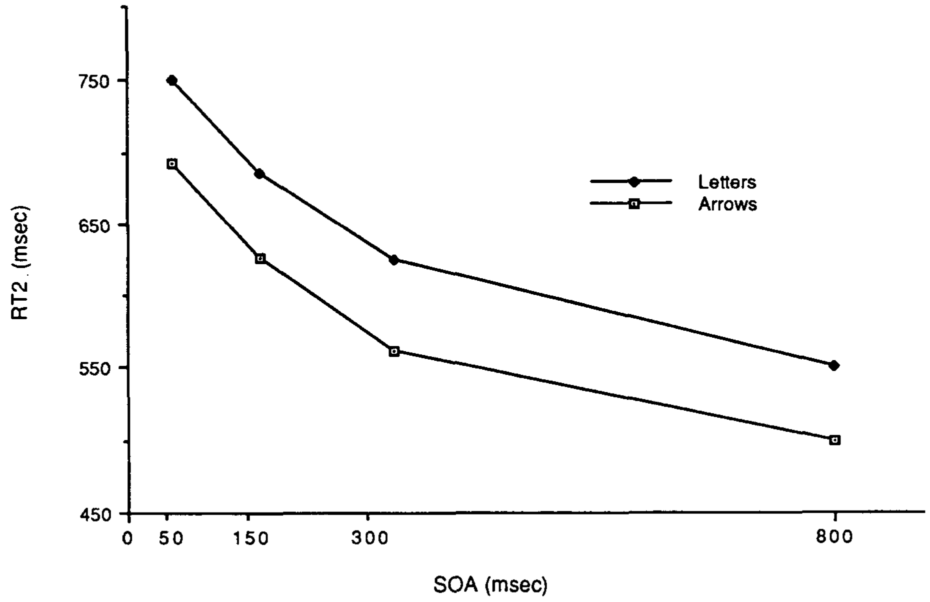

Figure 4. Mean response times (RTs) for Task 2 in Experiment 2 as a function of stimulus onset asynchrony (SOA) and symbolic compatibility (arrows vs. letters).

36 ms at the 800-ms SOA to only 3 ms at the 50-ms SOA. Thus, the Simon effect was strongly underadditive with task overlap, $F(3, 57) = 7.8, p < .001$.

Practice interacted significantly with task overlap: R2 slowing (RT2 at 50 ms minus RT2 at 800 ms) decreased from 226 ms on Day 1 to 162 ms on Day 3, $F(6, 114) = 3.67, p < .01$, replicating previous findings in the literature (e.g., Bertelson & Tisseyre, 1969). There was also a significant three-way interaction of spatial compatibility, symbolic compatibility, and task overlap, $F(3, 57) = 3.31, p < .05$. When Task 2 was performed by itself (i.e., at the 800-ms SOA), the Simon effect was more than twice as large for arrows (48 ms) as for letters (23 ms). As SOA decreased, and the Simon effect was reduced, this difference was reduced also.

Errors. Reported errors on Task 1 accounted for less than 2% of the responses, and no analyses were attempted. Table 2 presents mean error rates for Task 2 as a function of both forms of compatibility and SOA. Analysis of Task 2 error rates revealed a significant main effect for symbolic compatibility, $F(1, 19) = 20.18, p < .001$, reflecting greater accuracy

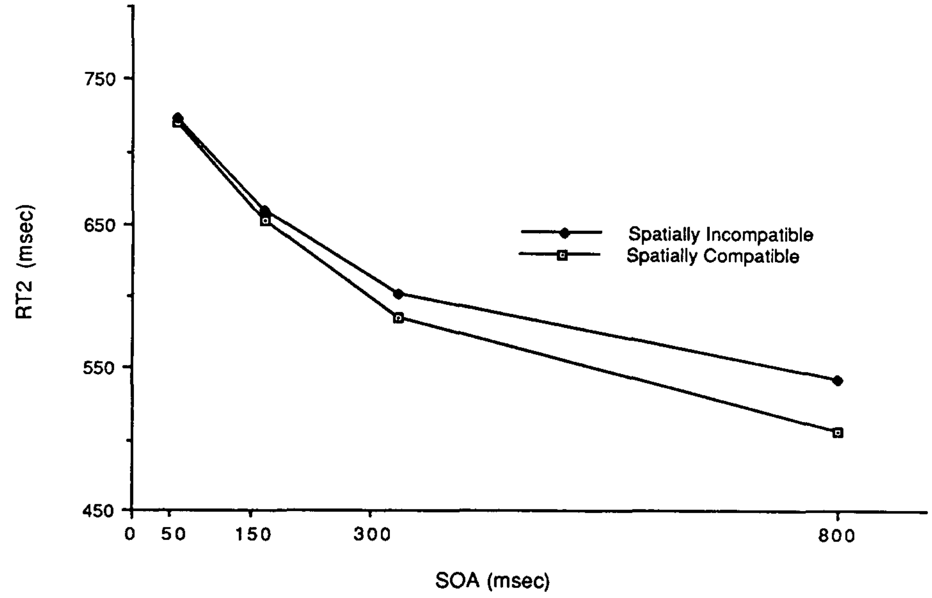

Figure 5. Mean response times (RTs) for Task 2 in Experiment 2 as a function of stimulus onset asynchrony (SOA) and spatial compatibility (the Simon effect).

Table 2
Task 2 Error Rates (%) in Experiment 2

Type of compatibility	Stimulus onset asynchrony (in milliseconds) 50	150	300	800
Symbolic				
Letters	4.9	6.2	5.8	6.4
Arrows	2.3	2.0	2.0	2.5
Difference	2.6	4.2	3.8	3.9
Spatial				
Noncorresponding	3.8	4.8	4.6	7.3
Corresponding	3.3	3.5	3.1	1.7
Difference	0.5	1.3	1.5	5.6

for arrows than for letters, and a significant main effect for spatial compatibility, $F(1,\ 19) = 21.4$, $p < .001$, reflecting greater accuracy for spatially compatible than for spatially incompatible trials. These factors also interacted significantly, $F(1,\ 19) = 10.47$, $p < .01$; the Simon effect was smaller for arrows than for letters, the opposite of the pattern in RT2.[4]

The only other significant interaction was between the Simon effect and SOA, $F(3,\ 57) = 9.56$, $p < .001$. At the 800-ms SOA, the error rate was substantially higher on spatially incompatible trials (7.3%) than on spatially compatible trials (1.7%). This difference decreased steadily across decreases in SOA and almost disappeared at the 50-ms SOA (3.3% for compatible trials vs. 3.8% for incompatible trials). By contrast, the interaction between the effects of symbolic compatibility and SOA did not approach significance, $F(3,\ 57) = 1.4$. In summary, the error pattern was the same as the RT2 pattern: The Simon effect was significantly reduced across SOAs, but the symbolic compatibility effect was not.

Discussion

The primary goal in Experiment 2 was to determine whether response selection would continue to function as a bottleneck when the S-R mapping required by Task 2 was made easier than in Experiment 1. An additional goal was to examine performance with more extensive practice. The most important result of Experiment 2 was that the effects of symbolic S-R compatibility were additive with the effects of task overlap (SOA); moreover, the additive pattern was unaffected by practice. A second interesting result was that the Simon effect interacted with task overlap. Unlike effects of symbolic compatibility, the Simon effect decreased steadily as SOA was reduced and was nearly eliminated at the shortest SOA.

Neither late-bottleneck (i.e., response initiation/execution) models nor capacity-sharing models can easily accommodate these results. If the bottleneck does not arise until response initiation/execution, both the Simon effect and the symbolic compatibility effect should have been underadditive with task overlap. Alternatively, if overlapping tasks interference was due to parallel processing of Tasks 1 and 2, but at a reduced rate owing to reduced capacity, both difficulty effects should have interacted overadditively with task overlap. No such pattern was observed.

The results are consistent with postponement models of dual-task interference, with a bottleneck at or before the response selection stage. Additivity of the effects of symbolic compatibility and SOA is strong evidence, following locus-of-slack logic, that response selection is not carried out during cognitive slack. The underadditivity between SOA and the Simon effect can be reconciled with the central-bottleneck model in either of two ways. One way is to accept the claims of Hasbroucq and Guiard (1991) and Stoffels et al. (1989) that the Simon effect is not an S-R compatibility effect at all, but rather has its locus in stimulus identification. If it is further assumed that stimulus identification occurs prior to the bottleneck (McCann & Johnston, 1989), locus-of-slack principles suggest that the effect would be absorbed into slack, yielding underadditivity.

The second way for a central bottleneck to yield an underadditive result follows the Simon et al. (1976) account of the loss of the Simon effect when delays were inserted between stimulus onset and response selection. For Simon et al., the Simon effect is the product of "an initial tendency to react to the location of the stimulus, rather than to its meaning" (p. 21). When the relative locations of the stimulus and the response do not correspond, the tendency activates a competing response, slowing down the selection of the correct one. The loss of the effect when response selection was delayed was attributed to a rapid dissipation of the "initial response tendency" following stimulus onset.

The central bottleneck model proposes that there is a delay somewhere between S2 and response selection. Thus, assuming that competing response tendencies activated by a stimulus decay quickly, the overlapping tasks paradigm provides the temporal conditions necessary for the effect to disappear. Note that the presence of delays is not a sufficient condition; we must also assume that "initial response tendencies" are generated independently of the bottleneck processor(s) and are therefore not subject to postponement. This assumption seems reasonable in light of the fact that competing response tendencies reflect an analysis of a stimulus attribute (location) that is irrelevant to task demands. The processing of irrelevant attributes is widely considered "automatic" (Garner, 1974; Kahneman & Treisman, 1984; McCleod & Dunbar, 1988), in the sense that such processing is triggered by the stimulus and runs to completion without the involvement of central processing mechanisms.

Our data do not allow us to distinguish between these two accounts. For present purposes, the important point is that on both accounts, cognitive slack, prior to response selection, is the source of the underadditive interaction. Thus, both accounts are consistent with a central-bottleneck model of dual-task interference.

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[4] The interaction of spatial compatibility and symbolic compatibility is interesting in its own right. To our knowledge it has not been measured previously within the same experiment (for similar manipulations across experiments, see Arend & Wandmacher, 1987). Because of the unfortunate signs that a speed–accuracy trade-off may have contaminated our measurement of the interaction, we do not consider further its theoretical implications.

General Discussion

The experiments reported here tested a postponement model of overlapping tasks interference with a central bottleneck at or before response selection. In Experiment 1 we manipulated the availability of a rule for mapping stimuli to responses. Effects of rule availability were additive with task overlap. In Experiment 2 we reduced the overall level of S-R translation difficulty relative to Experiment 1 and jointly manipulated the level of preexisting association between stimulus and response codes (i.e., symbolic compatibility) and whether or not the location of the stimulus concurred with the location of the response (i.e., spatial compatibility). Effects of symbolic compatibility were additive with task overlap. Moreover, the additive pattern persisted across three sessions of practice. By contrast, spatial compatibility (i.e., Simon) effects were sharply underadditive with SOA at all levels of practice.

Implications for Models of Overlapping Tasks Interference

These results have strong implications for existing accounts of R2 slowing in the overlapping tasks paradigm. According to capacity-sharing models (Kahneman, 1973; McCleod, 1977), R2 slowing reflects a reduction in the rate of processing of Task 2 that is due to task overlap. The natural prediction from these accounts is that Task 2 difficulty effects should be magnified at short SOAs. The present results conflict with these predictions; at short SOAs, the effects of Task 2 difficulty either remained constant or decreased; no increases were found. Similarly, in a recent report Pashler and Johnston (1989) found decreases rather than increases in stimulus quality effects at short SOAs. As we noted earlier, capacity theorists could argue that effects of stimulus quality are too peripheral to influence the capacity requirements of Task 2 and do not provide a fair test of capacity models. Because S-R compatibility influences processes that are clearly more central, the lack of overadditive patterns of interaction in the present experiments provides more conclusive evidence against capacity-sharing models.

Postponement models attribute R2 slowing at short SOAs to a processing bottleneck that forces delays in processing the later stages of Task 2. Two loci for the bottleneck have been suggested: a late bottleneck, so that only response execution is subject to postponement, and a central bottleneck, so that response selection and all subsequent processes are postponed.

The present results indicate that the locus of the bottleneck is central, occurring at or before the level of response selection, rather than in the final stage of response initiation/execution. According to the late-bottleneck model, response selection occurs prior to the bottleneck; thus, manipulations that affect S-R translation difficulty should be underadditive with task overlap. In fact, two manipulations of S-R translation difficulty (mapping rule availability in Experiment 1 and symbolic S-R compatibility in Experiment 2) showed an additive pattern instead.

The third factor, spatial compatibility (the Simon effect), yielded underadditive effects with SOA. There are at least two possible mechanisms by which a central bottleneck could produce this result. The standard mechanism (Pashler, 1984; Pashler & Johnston, 1989) assumes that the factor (in this case, incongruity between stimulus location and response location) affects a prebottleneck stage. Thus, factor-induced lengthening of the stage is absorbed into slack. The alternative mechanism postulates that slack provides time for "automatic" (that is, stimulus-driven) processes to dissipate, so that they lose their ability to interfere with processes that are subject to postponement.

The Nature of the Central Bottleneck

Our results provide strong evidence in favor of a bottleneck model of dual-task slowing in the overlapping tasks paradigm. Together with previous results (Pashler, 1989; Pashler & Johnston, 1989) they provide converging evidence that the bottleneck is central, somewhere between early stages of perceptual processing, such as stimulus encoding, and response initiation/execution. Can anything more precise be said about the locus of the bottleneck?

Figure 6 shows a simplified stage model of processing in choice RT tasks. Following Theios (1975) and Schwartz et al. (1977), we assume that central processing encompasses three discrete processes. The first process takes an encoded stimulus and attempts to match it with a template in memory (what Schwartz et al. refer to as the "memory comparison stage"). This produces a code corresponding to an identified stimulus. The large grey box in Figure 6 encompasses two processes commonly associated with the response selection stage. The first, abstract response code selection, takes as its input the identified stimulus code and applies an S-R translation rule (Duncan, 1977; Pashler & Baylis, 1991) to select an abstract response code. For example, in our Experiment 2, the input to this process might be an internal code corresponding to the letter M. The translation rule might take the following form: If M, then respond "left." Once the "left" code has been chosen, the second process retrieves the appropriate motor program (including a specification of the response effector), setting the stage for response initiation/execution.

In this framework, the bottleneck could be associated with one of the processes in the grey box or in a prior stage of stimulus identification. Beginning with the latest possible candidate and working forward, let us first consider the possibility that two motor programs cannot be retrieved simultaneously. In the present experiments, for example, it would not be possible to retrieve the program for the manual effector (Task 2) while simultaneously retrieving the articulatory code for "high" or "low" (Task 1). However, our results argue against this model. It seems unlikely that S-R compatibility effects are associated with motor program retrieval; most theories of S-R compatibility associate these effects with the earlier process of abstract response selection (cf. Kornblum, Hasbroucq, & Osman, 1990; Theios, 1975; Hasbroucq & Guiard, 1991). If so, and the bottleneck did not occur until motor program retrieval, locus-of-slack principles suggest that all of the difficulty effects in the present experiments would have interacted underadditively with SOA. Of course, they did not.

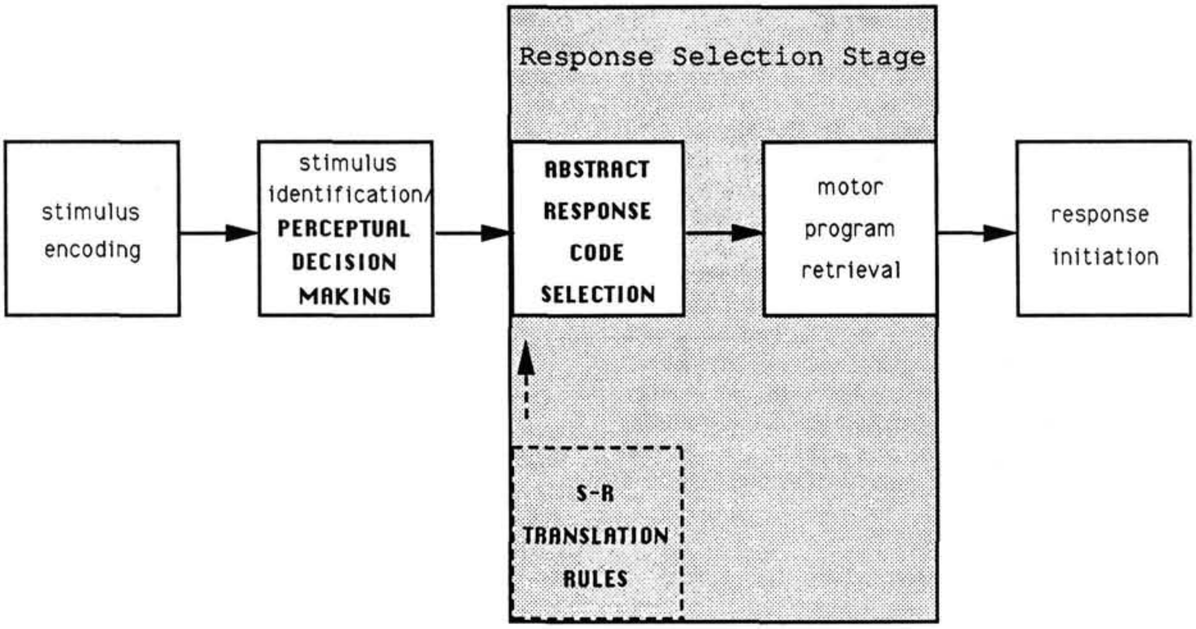

Figure 6. Stage analysis of choice reaction time tasks. (Processes in boldface are the most likely candidates for the central bottleneck.)

A more likely candidate is the abstract response selection stage. The bottleneck might occur here for at least two reasons. One is that only a single processor is capable of implementing S-R translation rules and the processor has the capacity to handle only one such operation at a time. Alternatively, the processor may be capable of carrying out S-R operations in parallel but be prevented from doing so because the two sets of S-R translation rules are not available simultaneously. Suppose, for example, S-R translation rules reside in an active (working) memory system that cannot store more than one set of rules at a time. Because Task 1 has priority, it is reasonable to assume that the rules for Task 1 would be loaded into the system first, leaving the Task 2 rules in an inactive state. Task 2 response selection would be prevented until the Task 1 translation rules were no longer needed and the Task 2 rules could be retrieved.

The final possibility is that the bottleneck emerges in perceptual processing, after stimulus encoding but before abstract response selection begins. For example, recent evidence (Johnston & McCann, 1991; McCann & Johnston, 1989) shows that certain forms of perceptual decision making, similar to the size classification required in Experiment 1, constitute a bottleneck. Other evidence (McCann & Johnston, 1989) shows that simple forms of stimulus identification, similar to the stimulus processing required in Experiment 2, are not subject to dual-task bottlenecks. Thus, it is possible that the bottleneck, while always central, may occur in either stimulus processing or abstract response selection depending on the difficulty level of the former. It is also possible that in complex tasks more than one processing locus forms a single-channel bottleneck. Further research will be needed to distinguish these possibilities.

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