

# Simultaneous Dual-Task Performance Reveals Parallel Response Selection After Practice

Eliot Hazeltine

National Aeronautics and Space Administration  
Ames Research Center

Donald Teague and Richard B. Ivry  
University of California, Berkeley

E. H. Schumacher, T. L. Seymour, J. M. Glass, D. E. Kieras, and D. E. Meyer (2001) reported that dual-task costs are minimal when participants are practiced and give the 2 tasks equal emphasis. The present research examined whether such findings are compatible with the operation of an efficient response selection bottleneck. Participants trained until they were able to perform both tasks simultaneously without interference. Novel stimulus pairs produced no reaction time costs, arguing against the development of compound stimulus–response associations (Experiment 1). Manipulating the relative onsets (Experiments 2 and 4) and durations (Experiments 3 and 4) of response selection processes did not lead to dual-task costs. The results indicate that the 2 tasks did not share a bottleneck after practice.

Performing two tasks at the same time can be extremely difficult. Psychologists have often visited this phenomenon to gain insight into the limits of human cognition. Why should the brain, considered the paragon of distributed computation, be so resistant to processing multiple, independent tasks in a parallel fashion? Whereas the dominant finding is that simultaneous execution leads to dramatic decrements in the performance of one or both tasks (see Pashler, 1998), some important exceptions to this principle have been described (e.g., Spelke, Hirst, & Neisser, 1976). However, in many of these exceptional cases, the level of analysis is not sufficiently sensitive to provide answers about how proficient dual-task performance is achieved. That is, the timing of the two tasks is not adequately controlled to determine whether critical task components temporally overlap or whether they are scheduled and executed serially.

Studies that have attempted to rigorously control the exact onset of task operations have revealed complex patterns of interference that are contingent on the particular task demands. The most common procedure is to separate the stimuli for the two tasks by a variable interval, termed the stimulus onset asynchrony (SOA). The basic finding is that as the SOA is shortened (i.e., bringing the stimulus onsets for the two tasks closer together), the reaction time (RT) for the second task increases. This phenomenon is called the psychological refractory period (PRP), because it suggests that a

period of time must elapse between the issuance of successive responses (Telford, 1931).

The robustness of the PRP has engendered a considerable body of research from which a fairly consistent picture has emerged. We briefly summarize the basic approach taken in PRP studies and review the dominant theoretical perspectives (for comprehensive reviews, see Meyer & Kieras, 1997b; Pashler, 1994a; Pashler & Johnston, 1998). Much of the PRP research has been aimed at identifying factors that influence the magnitude of the PRP effect. Factors presumed to affect stimulus-encoding processes on the second task produce larger increases in Task 2 RTs at long SOAs than at short SOAs. In contrast, factors presumed to lengthen response selection processes on the second task produce increases in Task 2 RTs that are constant across a range of SOAs. These data have been interpreted as the consequence of a central bottleneck (CB) that constrains performance so that response selection for the two tasks cannot be performed concurrently. The precise definitions of *response* and *task* are of course critical in the formulation of this hypothesis, and much work remains to be done to specify the boundaries of these terms. Nonetheless, if the existence of such a structural bottleneck could be established, it would embody a fundamental feature of the architecture of human cognition.

One criticism of the methodology used in PRP studies is that the relationship between SOA and RT on the second task is implicit in the task instructions (see Meyer & Kieras, 1997b; Meyer et al., 1995). That is, the instructions designate one task as primary, sometimes emphasizing that responses to this task should be made first. The delay between the first and second responses might also reflect strategic decisions made by participants to focus on the first task until it is completed. According to this account, RT patterns have little to do with the structural limitations of human cognition (Meyer & Kieras, 1997a). Although the PRP effect is robust when incentives are provided to decrease RTs on both tasks (e.g., Ivry, Franz, Kingstone, & Johnston, 1998; Ruthruff, Miller, & Lachmann, 1995), this issue has proven difficult to resolve. Given that the goals of one task may conflict with the goals of another task, serial performance may be a generally advantageous strategy and, as such, may be difficult to overcome (Simon, 1994).

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Eliot Hazeltine, National Aeronautics and Space Administration (NASA) Ames Research Center, Moffett Field, California; Donald Teague and Richard B. Ivry, Department of Psychology, University of California, Berkeley.

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Correspondence concerning this article should be addressed to Eliot Hazeltine, NASA Ames Research Center, Mail Stop 262-4, Moffett Field, California 94035. E-mail: ehazeltine@mail.arc.nasa.gov

Evidence that the bottleneck is strategic rather than a structural feature of human cognition has been obtained with PRP designs (Meyer et al., 1995; Schumacher et al., 1999). The basic result in these studies was that factors presumably affecting response selection on Task 1 led to smaller RT costs on Task 2 at shorter SOAs than at longer SOAs. This pattern of data implies that response selection processes for the two tasks were occurring in parallel on trials with short SOAs, contrary to the central tenet of CB models. However, in these experiments, considerable interference was still observed at the shorter SOAs, suggesting that there may exist an additional bottleneck, possibly related to response initiation, and that some components of response selection may be processed in parallel (see also De Jong, 1993; Ivry et al., 1998).

Most PRP studies have been conducted with relatively unpracticed tasks. The CB model was developed to account for such performance (see Pashler, 1998), and the results under such conditions are highly consistent with the predictions of the model. Less explored has been the relevance of the model in describing the performance of practiced participants. From the structural limitation view embodied by the CB model, one might suppose that such limitations remain intact, even though practice reduces the time required for the various processing stages and as such attenuates or, under the right conditions, obscures dual-task interference (Van Selst, Ruthruff, & Johnston, 1999). Alternatively, if PRP effects are primarily strategic and strategies become optimized with practice, then it should be possible for participants to develop strategies that obviate the need for any shared processing between two carefully selected tasks.

The effect of practice in PRP studies has been the focus of a number of recent investigations. In a series of elegant experiments, Van Selst et al. (1999) and Ruthruff, Johnston, and Van Selst (2001) tested the PRP effect over an extended period of practice. Unlike previous training studies in which manual responses were required for both tasks (e.g., Karlin & Kestenbaum, 1968; Van Selst & Jolicœur, 1997), these researchers used an auditory–vocal task and a visual–manual task. These pairings ensured that the stimulus and response processes invoked by the two tasks were as distinct as possible. Although the PRP effect was dramatically reduced after practice, it remained robust. There was evidence, however, that processes that had initially been performed sequentially were being performed in parallel after practice (see also Schumacher et al., 1999). Nevertheless, after extensive training, RTs for the second task at the shortest SOA were still 40 ms longer than those at the longest SOA.

A second critical finding was that the reduction in the PRP effect was largely determined by the reduction in the overall RT for Task 1; practice on Task 2 had little effect on the size of the PRP effect. This result is consistent with the CB model. If delays on Task 2 occur because the response selection bottleneck is engaged by Task 1, then the duration of this process for Task 1 should largely determine the magnitude of the PRP effect.<sup>1</sup> That this bottleneck is the major target of practice effects is also reasonable in these studies given that the stimuli were very discriminable and required simple overt responses. We would expect practice to predominantly facilitate response selection, because it is this stage that constitutes the novel aspect of the tasks. In summary, these training studies demonstrate that although the component operations can be made more efficient, the basic constraints on performance remain in place.

Recently, Schumacher, Seymour, Glass, Kieras, and Meyer (2001) provided strong evidence that, after considerable practice, two tasks can be performed simultaneously with little cost to either. They also used auditory–vocal and visual–manual tasks to minimize the overlap at more peripheral processing stages associated with stimulus identification and response execution. Most important, they provided instructions and incentives that were designed to encourage equal treatment of both tasks. To further emphasize the equal status of the two tasks, Schumacher et al. used only a 0-ms SOA (simultaneous presentation) rather than a set of varying SOAs as in traditional PRP experiments. The results were striking: Under these conditions, dual-task performance was essentially identical to that observed in single-task trials. These findings differ from the persistent dual-tasks costs observed by Ruthruff, Pashler, and Klaassen (2001), whose study involved a similar paradigm but participants who were less practiced.

As an alternative to the CB model, Meyer and Kieras (1997a) proposed the executive process/interactive control (EPIC) model to account for the control of task operations in dual-task situations. According to EPIC, distinct sets of production rules can be applied simultaneously for separate tasks, and there is no bottleneck associated with response selection. So that task operations occur in an adaptive, coordinated manner, an executive process establishes priorities and strategically schedules the flow of information to satisfy the task instructions and reduce competition for peripheral mechanisms such as the controllers of the eyes and hands. When one of the tasks is regarded as primary by the executive control process, delays are imposed on processes relating to the secondary task to ensure that there are no conflicting demands for peripheral resources. A PRP-like RT pattern emerges from the increased need for the delays at shorter SOAs.

The results of Schumacher et al. (2001) are consistent with the EPIC model, according to which the operations for certain tasks can be completely independent after extensive practice. When neither task is given priority and the stimuli are presented simultaneously, these segregated operations can occur in parallel; there is no shared CB limiting processing. However, the CB model may be able to account for the Schumacher et al. results as well. There are at least two possible explanations for these findings that are consistent with the proposal that the CB remains intact even after extensive practice. First, the bottleneck processes for the two tasks might not overlap when the SOA is zero. After extensive practice, such processes for visual–manual and auditory–vocal tasks may be fairly short (Ruthruff, Johnston, & Van Selst, 2001; Van Selst et al., 1999) and may not overlap owing to differences in the durations of prebottleneck components for the two tasks. This account could certainly lead to largely reduced interference, even though a CB would still be in effect. We addressed this possibility in Experiments 2–4.

The second hypothesis, explored in Experiment 1, is that, with practice, the two tasks are reconfigured such that they constitute a single task with a complex stimulus–response (S-R) mapping. That is, the auditory and visual stimuli may be treated as a compound stim-

<sup>1</sup> The length of the stimulus classification processes for both Task 1 and Task 2 also contributes to the magnitude of the PRP (see Ruthruff, Johnston, & Van Selst, 2001); if one assumes that these processes remain fairly constant across practice, however, response selection for Task 1 should primarily determine the size of the effect.

ulus, and the vocal and manual responses may be treated as one compound action. Indeed, the fact that the stimuli were always presented simultaneously in Schumacher et al. (2001) might have promoted a strategy in which the two tasks were viewed in a unified manner. Note that single-task trials could be treated as just another member of the S-R set in this conceptualization of the task, with combinations including no visual stimulus trials (and no manual response) and no auditory stimulus trials (and no vocal response). If, after extensive practice, participants were able to organize performance of the task in this way, then the results reported by Schumacher and colleagues would be completely consistent with bottleneck accounts. In short, according to this explanation, no interference is observed because, in effect, only one task is being performed.

## Experiment 1

The purpose of the first experiment was twofold. First, we wished to replicate the results of Schumacher et al. (2001) and track the performance changes that occur as people become proficient in performing two simultaneous tasks. In studies involving the PRP paradigm, decrements in the PRP effect have closely tracked the reduction in RTs for one of the tasks. In the present experiment, we examined the relationship between reductions in dual-task costs and single-task RTs to determine whether performance can be accounted for solely by a shortening of the single-task operations.

The second goal was to determine whether, after extensive practice, participants treat the stimuli and responses for both tasks as a single S-R compound for the purposes of response selection. For the auditory-vocal task, one of three sounds was presented, and participants gave a vocal response based on the pitch of the stimulus. For the visual-manual task, a visual stimulus appeared at one of three spatial positions, and participants responded manually using one of three response keys. On dual-task trials, a sound and a visual stimulus were presented simultaneously. Thus, there were nine possible combinations of the auditory and visual stimuli. During the initial training, only six of these pairs were presented. After the participants had achieved dual-task performance that was approximately equivalent to single-task performance, the novel three stimulus pairs were introduced. If participants learned to treat the stimulus pairs as a single task, the new combinations should be unpracticed and therefore processed more slowly than the practiced pairs.

## Method

**Participants.** Nine participants were trained to perform two tasks: a visual-manual task and an auditory-vocal task. They were seated in a dimly lighted room 60 cm from a desktop computer. They were paid for their participation at a rate of \$8 per hour plus performance-based bonuses.

**Apparatus and stimuli.** For the visual task, participants responded manually to a white circle that appeared in one of three locations arranged horizontally across the black background of a computer monitor. Each circle subtended approximately 1° of visual angle, and the possible locations were separated by approximately 0.8° of visual angle. Three white lines that served as placeholders for the possible locations were continuously present on the screen, approximately 0.5° below the location of the circles. The circle remained visible until the participant responded or until a 2,000-ms interresponse interval had expired. Participants responded to the circles by making a spatially compatible keypress with the index, middle, and ring fingers of their right hands. The responses were collected with a response board connected to the computer.

For the auditory task, participants responded vocally to tones played from the computer's internal speaker. The tones lasted 150 ms and were 220 Hz, 880 Hz, or 3520 Hz in frequency. Participants responded according to the frequency by saying "one," "two," and "three" for the low-, middle-, and high-pitched sounds, respectively. The participants' vocalization activated a voice key, also connected to the computer, so that an accurate measurement of vocal RT could be acquired. The experimenter typed the actual response on the computer keyboard so that accuracy could be assessed.

**Procedure.** The procedure essentially duplicated that of Schumacher et al. (2001). There were two types of trial blocks: single-task blocks and dual-task blocks. During single-task blocks, participants performed 45 trials of either the visual or auditory task. Thus, there was no uncertainty about which type of trial was to be performed throughout the single-task blocks. During dual-task blocks, participants performed a mixture of 30 single-task trials (15 for the visual task and 15 for the auditory task) and 18 dual-task trials. The order of these trials was randomized. On the dual-task trials, participants were presented with a visual and auditory stimulus simultaneously. They were instructed to respond to both as quickly as possible. Adopting the nomenclature chosen by Schumacher et al. (2001), we labeled trials occurring in the single-task blocks *single-homogeneous* (S-Hom) trials and single-task trials occurring in the dual-task blocks *single-heterogeneous* (S-Het) trials. In the present experiment, the remaining dual-task trials were divided into combinations of stimuli that appeared during training, termed *dual-old* (D-Old) trials, and combinations that appeared only during the transfer session, termed *dual-new* (D-New) trials.

The two types of dual-task trials represented a critical difference from the Schumacher et al. (2001) procedure. In the present experiment, training on dual-task blocks consisted of a subset of the possible circle-tone combinations. Six of the nine possible pairings were presented during the training sessions. The three combinations that were withheld varied across participants to ensure that any differences between the old and new combinations did not result from idiosyncrasies of particular stimulus pairs. The old and new sets were created so that each tone and each location remained equally likely between the two sets. During transfer sessions, all nine auditory-visual combinations were presented during the dual-task blocks. The introduction of the new combinations required longer blocks, so the length of the blocks was increased to include 30 single-task trials and 27 (18 D-Old and 9 D-New) dual-task trials. Thus, all combinations of stimuli were equally likely during the transfer sessions.

The instructions were designed to encourage participants to perform the tasks as quickly and accurately as possible at all times during all blocks. They were told not to respond in any particular order and to give equal priority to both tasks. A payment scheme was devised to reinforce accurate and fast performance. To explicitly establish ideal levels of performance, we determined target times for each participant. Separate target times were computed for single- and dual-task blocks and, within the blocks, for manual and vocal RTs. The target times were equal to the mean RTs on the single-task trials (S-Hom for single and S-Het for dual). The dual-task trials played no role in the bonus payment criteria, although the participants received bonuses for both single-task and dual-task blocks based on these criteria. As a means of ensuring that the participants continually sought to respond as quickly as possible, the target times were reduced whenever the mean RT for a particular condition was lower than the corresponding target time.<sup>2</sup>

<sup>2</sup> When participants' RT for a given block was less than 100 ms greater than the corresponding target time, they received an additional 10 cents for that block. When the RT was less than 50 ms, they received an additional 25 cents. Finally, when the RT was faster than the target time, they received an additional 50 cents, and the target time was reset to the new, faster value. Note that on dual-task blocks, participants earned separate bonuses based on the two tasks and that the target times were adjusted independently. Both types of blocks included bonus payments made on the basis of accuracy, so one-half cent was given for each correct response and 5 cents were deducted for each incorrect response.

Participants performed multiple sessions of the two tasks during training. When possible, sessions were scheduled on consecutive days. All participants completed the training within 2 weeks. On the first session, participants began with 6 introductory blocks consisting of 2 single-task blocks of each type and 2 dual-task blocks. The single-task blocks were always performed first, but the order of these initial blocks was counterbalanced across participants. After completing these 6 blocks, participants performed 2 single-task blocks of each type and 6 dual-task blocks. Each subsequent session proceeded as follows: Participants began with 2 single-task blocks (1 of each type) and then 12 blocks consisting of 4 single-task blocks (2 of each type) and 8 dual-task blocks. Excluding the initial 2 single-task blocks, single-task blocks were always separated by 2 dual-task blocks. The actual order of the blocks was pseudorandomized across participants and sessions. Transfer sessions were identical to training sessions, except that the dual-task blocks contained an additional nine dual-task trials, consisting of the new combinations. All other aspects were the same, and participants were not told of the transition from the training to transfer sessions.

Participants were trained with varying amounts of practice to determine whether they could acquire levels of performance under dual-task conditions that were identical to those achieved under single-task conditions. Once a participant's RTs for all three trial types (S-Hom, S-Het, and D-Old) were within 15 ms of each other on the visual task and within 20 ms of each other on the auditory task, she or he was moved to the transfer sessions in which the new dual-task pairings were introduced. For all of the analyses, RTs that were three standard deviations from the mean were removed from the data. Trimming the data according to this criterion removed less than 1% of the RTs for both the visual and auditory tasks.

### Results and Discussion

**Dual-task performance.** According to the criteria established by Schumacher et al., 7 of the 9 participants were able to achieve almost zero dual-task interference by their eighth session (mean: 6; minimum: 5) and were advanced to the transfer sessions. The remaining 2 participants began the transfer phase after their seventh and eighth sessions, respectively, without having met the criteria. Our primary analysis focused on performance during the two transfer sessions. Because the S-Hom trials were unique in that participants were able to anticipate trial type on these pure blocks, comparisons between D-Old and S-Het trials served as the preferred measure of dual-task costs.

For the analysis of dual-task performance, the data were pooled across the two transfer sessions. Mean RTs for each trial type and participant were computed after elimination of trials with incorrect responses on either task. The resulting mean RTs (Figure 1) were submitted to a one-way analysis of variance (ANOVA) with trial type (S-Hom, S-Het, D-Old, or D-New) as the factor and participant as the repeated measure. There was no effect of trial type for either the visual task,  $F(3, 24) < 1$ ,  $MSE = 97.75$ , or the auditory task,  $F(3, 24) = 2.23$ ,  $p > .10$ ,  $MSE = 110.71$ .

Identical analyses were performed on the accuracy data (Figure 1). There was a significant effect of trial type for the visual task,  $F(3, 24) = 3.82$ ,  $p < .05$ ,  $MSE = 0.001$ , but not for the auditory task,  $F(3, 24) < 1$ ,  $MSE = 0.001$ . Examination of the cell means for the visual task indicated that participants were least accurate during the blocks of homogeneous single-task trials, suggesting that the effect was not related to a cost of performing the two tasks simultaneously. The decreased accuracy on the single-task blocks may have reflected reduced attentiveness due to the reduced processing demands in this condition. Importantly, accuracy was similar on the S-Het and dual-task trials.

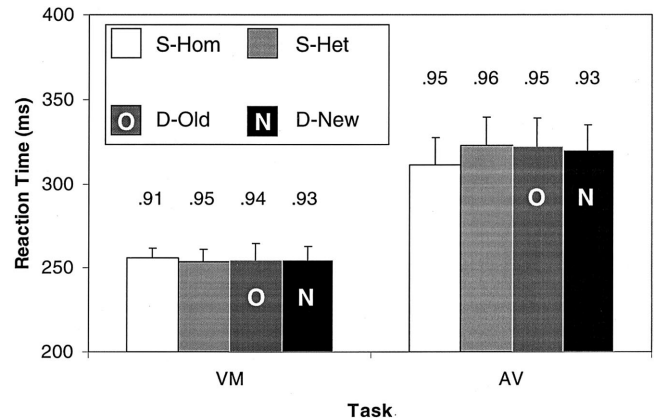


Figure 1. Experiment 1: Mean reaction times for the four trial types on visual (VM; left) and auditory (AV; right) tasks. The proportions of correct responses for the four trial types are shown above the appropriate columns. S = single; Hom = homogeneous; Het = heterogeneous; D = dual.

These results indicate that, similar to the findings of Schumacher et al. (2001), participants were able to achieve levels of performance under dual-task conditions that were similar to those obtained under single-task conditions. After no more than eight training sessions, the mean costs were essentially 0 ms for the visual task and a nonsignificant 10 ms for the auditory task. Such findings differed from those acquired with the standard PRP design in which the two stimuli appear sequentially. For example, using a similar pair of tasks, Van Selst et al. (1999) observed a PRP effect of nearly 50 ms after even more extensive training than that provided here. In contrast, the present results demonstrated that two tasks can be performed simultaneously with little evidence of any decrement in performance for either task. We expect the discrepancy reflects the fact that the stimuli were presented simultaneously throughout training in our study, with no priority given to either task, whereas the stimuli appeared sequentially with one task always presented first in the Van Selst et al. study.

The lack of dual-task costs does not appear to reflect the learning of compound S-R associations. Performance on trials with new combinations of stimuli was nearly identical to performance on trials with trained combinations of stimuli. Not only were the new combinations of circles and tones performed as well as combinations that had been practiced over many previous sessions, but these new combinations were also performed as well as the single-task trials. This result argues against the hypothesis that dual-task costs were avoided by combining the two response selection processes into a single compound selection. Instead, it appears that response selection occurs independently and in parallel for the two tasks. It is possible that participants learned the new combinations of stimuli by generalization; that is, training on a restricted set of combinations transferred to performance on all combinations. If such ability can be demonstrated, it would embody an important feature of S-R learning (cf. Pashler & Baylis, 1991). This possibility was addressed in Experiment 2.

**Time course of training.** We examined the data at three periods to track the participants' dual-task performance over the course of training. The first period, termed early, was defined as the second and third sessions. Because participants differed in the

rate at which they achieved dual-task performance, the remaining two phases were identified according to behavioral criteria rather than session number. The late period was defined as the two sessions performed before the criteria for dual-task performance were met. The final period consisted of the two transfer sessions described earlier.

These data were submitted to a two-way ANOVA in which one variable represented time period and the other variable represented trial type: S-Hom, S-Het, or D-Old. Because the D-New trials occurred only during the final time period, these data were not included in the analysis. There were significant Period  $\times$  Trial-Type interactions for both the visual,  $F(4, 32) = 5.57, p < .01, MSE = 276.55$ , and auditory,  $F(4, 32) = 4.42, p < .01, MSE = 187.90$ , tasks, indicating that the decrease in RTs on dual-task trials was greater than that observed on single-task trials. The means for the two tasks are shown as a function of training in Figure 2.

The greater reductions in RTs for the dual-task trials were expected, because they reflect the fact that, initially, participants demonstrated a clear dual-task cost that they were able to overcome with practice. In other words, efficient performance on the dual-task trials requires practice. For the visual task, the RT reductions from early in training to the test sessions were 17, 32, and 67 ms for the S-Hom, S-Het, and D-Old trials, respectively. For the auditory task, the reductions were substantially larger: 114, 120, and 145 ms for the S-Hom, S-Het, and D-Old trials, respectively. It is not possible to determine at which processing stage these benefits occur. However, the difference in the magnitude of the practice effects for the two tasks suggests that response selection for the auditory task was initially more difficult than selection for the visual task. This finding is also in accord with the fact that the S-R mapping for the auditory task was less compatible than the mapping for the visual task.

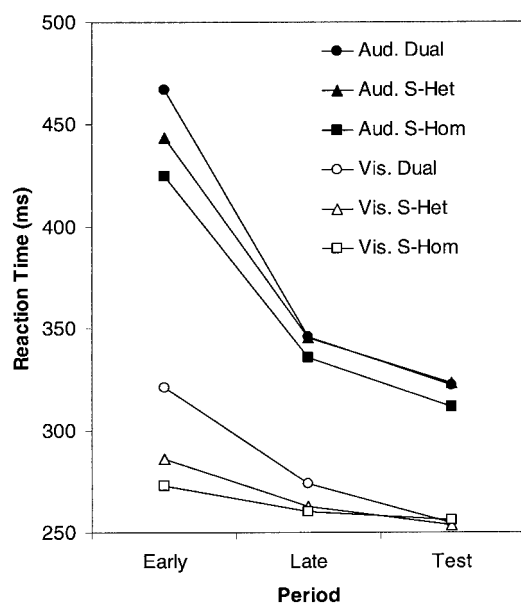


Figure 2. Experiment 1: Mean reaction times for the two tasks, shown as a function of training. Aud. = auditory; S = single; Het = heterogeneous; Hom = homogeneous; Vis. = visual.

**Correlations.** An alternative analytic approach is to look at the trial-by-trial correlations in RTs for the visual and auditory tasks. In dual-task experiments with short (or 0-ms) SOAs, correlations in RTs have been observed between the two tasks, a result that has been interpreted as reflecting the requirement that CB processes for the second task cannot take place until they have been completed for the first task (e.g., Pashler, 1994b). Thus, speedups or delays in completing CB processes on the first task lead to corresponding speedups or delays on the second task. We have outlined two ways in which the CB model could account for the lack of dual-task costs after extended practice, one based on the idea of nonoverlapping response selection and the other based on the idea of task reconfiguration. Both of the CB-based hypotheses make the same prediction regarding trial-by-trial correlations: If the two tasks successively access the CB in a consistent order, then RTs for the visual and auditory tasks should be positively correlated. Regardless of whether one assumes that CB processes for the two tasks are staggered or that they are combined into a single process, this positive correlation should be obtained. In the former case, the correlation is expected because delays in the operation of the CB for Task 1 should delay the availability of the CB for Task 2. In the latter case, the two responses are based on the joint operation of the CB, and changes in the duration of this computation should apply to both tasks. In contrast, if the two tasks are truly performed independently, then the correlation between RTs on dual-task trials should be near zero.

To examine this issue, we calculated the correlation between RTs for the visual and auditory tasks on the dual-task trials for each participant. For the test sessions, the correlations were weak but significantly greater than zero for both the trained pairs and untrained pairs: D-Old ( $M = .21, SD = .17, t(8) = 3.58, p < .01$ , one-tailed), and D-New ( $M = .18, SD = .17, t(8) = 3.09, p < .01$ ). The slopes calculated for the regression were also unimpressive: The mean slope for the D-Old trials was  $.28 (SD = .26)$ , and the mean slope for the D-New trials was  $.21 (SD = .21)$ . These correlations were smaller and the slopes shallower than those reported in PRP experiments (e.g., Pashler & Johnston, 1989; Van Selst et al., 1999; see also Pashler, 1994a). Nonetheless, these findings could be accommodated by the CB model if postbottleneck processes contributed most of the variability to the RTs.

In summary, the results of Experiment 1 are highly consistent with those reported by Schumacher et al. (2001). It appears that the participants were able to perform the two tasks simultaneously and independently: There were no significant costs on dual-task trials relative to single-task trials, and the RTs for the two tasks were only weakly correlated. Most striking, performance on new combinations of stimuli was no different from that on highly trained combinations, suggesting that the S-R associations for the two tasks were segregated throughout training. It is possible that a combined response selection was performed but that learning generalized to novel sets of combinations. In Experiment 2, we tested this explanation by further examining the independence of the response selection processes for the two tasks.

## Experiment 2

The lack of a dual-task cost for either the old or new stimulus combinations in Experiment 1 argues against the reconfiguration hypothesis. Nonetheless, some features of the data warrant caution

before concluding that the CB model does not provide an adequate description of the performance of highly practiced individuals. Dual-task RTs on the visual task were, on average, 66 ms faster than those on the auditory task. In fact, the responses on the visual task occurred before the responses on the auditory task on 90% of the dual-task trials. Although our instructions emphasized equal priority to the two tasks, it is possible that the participants were using a sequential strategy when performing the tasks. Participants could have been selecting the response for the spatially compatible visual task first and then selecting the response for the auditory task. If the selection process for the visual task was completed before the onset of the selection process for the auditory task, then there would be little overlap in terms of when the two tasks engaged the response selection bottleneck (Figure 3A). Thus, the costs associated with a bottleneck would be minimal.

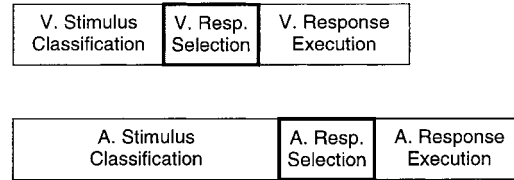
An alternative form of the configuration hypothesis that is consistent with the response selection bottleneck hypothesis was alluded to in the discussion of Experiment 1. It is possible that a single response selection process simultaneously selects the vocal and manual responses by treating the visual and auditory tasks as a single, compound task. No costs were observed for the new combinations of auditory and vocal stimuli, possibly because the appropriate responses for these trials were inferred from exposure to the practiced combinations (cf. Pashler & Baylis, 1991). Again, we would expect the correlation between the RTs for the two tasks to be somewhat stronger than what was observed, but relatively high variance in postselection stages may have prevented this prediction from being borne out.

These two explanations share a common prediction: Delaying response selection for the faster visual task should slow RTs on the slower, auditory task. As depicted in Figure 3, increasing the processing time required before the bottleneck for the fast task should introduce overlap in terms of when the two tasks require access to the selection process. This increase would lead to an increase in RT for both tasks if the two tasks sequentially accessed the response selection bottleneck (Figure 3B).<sup>3</sup>

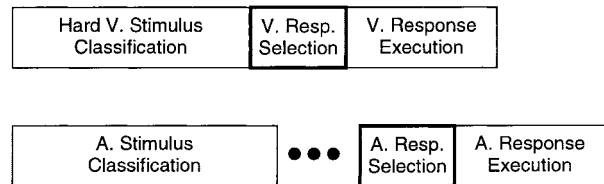
There are two possibilities to consider if response selection occurs in a compound manner for the two tasks. First, the RTs for both tasks might become slower because the processing time before selection is increased (Figure 3C). Second, there may be little observed increase in the RT for the visual task. This would occur if the extra processing time required for this task is absorbed into the *slack* (Pashler & Johnston, 1989) created by the longer auditory stimulus classification (Figure 3D). In either case, the compound selection model does not predict that prolonging visual stimulus classification will produce larger effects on visual RT than on auditory RT.

In contrast, this is exactly the prediction one would make if the two tasks were performed independently: Manipulating the processing requirements for the faster task should have no effect on the slower task. Thus, by delaying response selection on the visual task, we should be able to pit the CB model against the independent selection hypothesis. To delay the selection processes, we borrowed a manipulation frequently used in PRP studies: changing the discriminability of the stimuli. Discriminability is assumed to primarily affect perceptual identification, a process that must be completed before response selection can begin (Pashler & Johnston, 1989). Therefore, reducing the discriminability of the stimulus should postpone the onset of response selection.

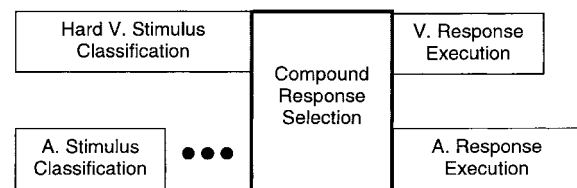
#### A. No dual-task cost due to nonoverlapping selection



#### B. Long classification, short selection



#### C. Short auditory classification, combined selection



#### D. Long auditory classification, combined selection

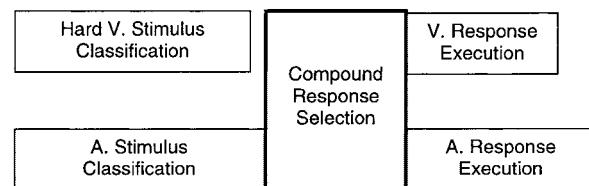


Figure 3. Stages of processing depicted for the two tasks in Experiment 2. A: Response selection for the visual task occurs before selection for the auditory task, minimizing interference. B: Selection is delayed for the visual task by lengthening stimulus classification processes, pushing it into conflict with selection for the auditory task. C: Delays induced by lengthening classification for the visual task are conferred to the auditory task when a compound selection process is used. D: Lengthening of stimulus identification for the visual task is absorbed into the slack created by the compound selection process, which must not begin until auditory stimulus identification is completed. V. = visual; Resp. = response; A. = auditory.

Our focus in Experiment 2 was to test the hypothesis that the lack of a dual-task cost in Experiment 1 occurred because the

<sup>3</sup> It is possible that, when the visual task is made harder, the order in which the two tasks access the selection process might be reversed. Thus, we might find little dual-task cost because selection for the auditory task is always completed before the visual task. Although unlikely, we examined this hypothesis in Experiment 4.

participants were able to complete the CB operation for the visual task before the point at which this operation was required for the auditory task. Given this, we opted to recruit the participants from Experiment 1 for Experiment 2 and, indeed, continued with this strategy in Experiments 3 and 4. As such, any comparisons between experiments must be treated with caution because the participants could have benefited from the accumulating effects of extended practice. Nonetheless, by continuing with the same set of participants, we could evaluate whether the introduction of the discriminability manipulation introduced a dual-task cost. We also included a condition identical to that used in Experiment 1. We expected that the near-perfect dual-task performance in this condition would be sustained.

### Method

**Participants.** Experiment 2 was performed by 7 of the 9 individuals who participated in Experiment 1, including one of the individuals who did not meet the dual-task performance criteria during the training portion of the previous experiment. Note that examination of this participant's data revealed that he had achieved the dual-task performance criteria by the final test session.

**Stimuli.** With one exception, the stimuli were identical to those used in Experiment 1. For half of the trials that included the visual task, the visual stimuli were identical to those used in Experiment 1. For the other half of the trials that included the visual task, the target circle was presented with two distractor circles in the remaining stimulus locations. The distractor circles were 69.5 cd/m<sup>2</sup>, whereas the target circle was 26.4 cd/m<sup>2</sup>. Participants were not able to predict whether the distractor circles would appear on any given trial, but their task was to respond to the dimmer stimulus. Trials in which the target stimulus was presented alone were termed *easy*. Trials in which the target was presented with distractors were termed *hard*, because they involved a more difficult visual discrimination. The difference in brightness between the target and distractors was well above threshold. Nonetheless, the difficult condition involved a discrimination judgment in terms of both brightness and location, whereas the easy task required only a discrimination of location.

**Procedure.** For 6 of the participants, there was no break between the transfer sessions of Experiment 1 and the test sessions of Experiment 2. For the other participant, a break of almost 6 months separated the two experiments. This participant was first retested on three transfer sessions of Experiment 1. Once performance on the dual-task trials matched that achieved on single-task conditions (according to the criteria from Experiment 1), the participant performed two test sessions for Experiment 2. The pattern of data for this individual was highly similar to that for the other participants.

The test sessions were similar to those used in Experiment 1 with the addition of the easy–hard manipulation of the visual task. This doubled the number of required visual trials in each block. To maintain the probabilities of Experiment 1, we also doubled the number of single-task auditory trials in both the single- and dual-task blocks. Thus, the blocks contained twice as many trials (90 trials per single-task block and 114 trials per dual-task block, with 54 of these dual-task trials). Participants completed four single-task blocks (two auditory and two visual) and nine dual-task blocks in each of the two sessions.

All of the possible combinations of stimuli were used for the dual trials during both the training and test sessions. Therefore, the new–old distinction used in Experiment 1 was abandoned, and all of the dual-task trials were aggregated. All other aspects of the procedure were identical to Experiment 1.

### Results and Discussion

**Dual-task performance.** Dual-task performance was assessed as in Experiment 1, except that a new factor, stimulus discriminability, was added to the ANOVA. The RTs and error rates for each of the three trial types in each of the two discriminability conditions are shown in Figure 4. For the visual task, depicted in the top panel, there were significant effects of trial type,  $F(2, 12) = 10.42$ ,  $p < .01$ ,  $MSE = 90.89$ , and discriminability,  $F(1, 6) = 158.44$ ,  $p < .01$ ,  $MSE = 178.21$ . The effect of discriminability indicated that participants were faster on easy trials (286 ms) than on hard trials (338 ms). Thus, our manipulation of discriminability was effective.

The effect of trial type was due to RTs being slowest when the visual task was performed alone (S-Hom blocks). This finding mirrored the decrease in accuracy for the corresponding condition in Experiment 1. This decrement in performance may reflect a change in participants' strategy or level of motivation between the single- and dual-task blocks.

The difference between easy and hard discriminations for the visual task was identical for the S-Hom and S-Het trials: 49 ms. For the dual-task trials, the difference was 57 ms, producing a significant Trial-Type  $\times$  Discriminability interaction,  $F(2, 12) = 6.28$ ,  $p < .05$ ,  $MSE = 11.69$ . CB models cannot readily account for the fact that, on dual-task trials, the cost associated

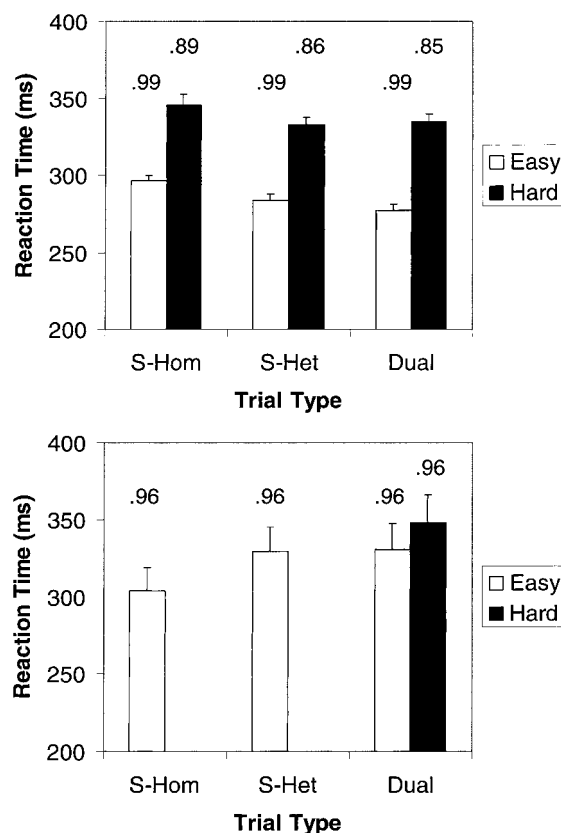


Figure 4. Mean reaction times and proportions correct for the visual task (top) and auditory task (bottom) in Experiment 2. S = single; Hom = homogeneous; Het = heterogeneous.

with hard discriminations was greater than the cost associated with easy discriminations. The reason is that the discriminability manipulation is thought to affect stimulus-encoding processes, which are presumed to occur before the bottleneck. If selection for the visual task were occurring before selection for the auditory task, then the costs would be identical for both trial types. If selection for the visual task were occurring after selection for the auditory task, then the added processing required for the hard discrimination could take place during auditory selection. Such an arrangement would produce smaller costs for the dual-task trials. Thus, the interaction is more consistent with a limited resource model of dual-task performance. However, it should be noted that the RTs for the hard S-Het and dual-task trials were essentially identical, and the interaction was driven by slower RTs for the easy S-Hom trials. Therefore, the small difference (8 ms) in discrimination costs may have resulted from participants altering their strategies during the single- and dual-task blocks.

For the auditory task, the analyses could not be performed in an analogous fashion because, unlike the dual-task trials, the single-task trials did not have two levels of discriminability for the visual stimulus. For this reason, the data were submitted to two separate ANOVAs. In the first ANOVA, we included the single-task auditory conditions (S-Hom and S-Het) and the dual-task conditions in which the auditory stimulus was combined with the easy visual discrimination task. The purpose of this analysis was to determine whether there were any costs associated with having to perform the two tasks simultaneously. Note that because we limited this analysis to the easy visual trials, the analysis essentially involved a replication of conditions from Experiment 1. The analysis revealed a highly significant effect of trial type,  $F(2, 12) = 25.77, p < .01, MSE = 60.89$ , reflecting the fact that S-Hom trials were performed nearly 27 ms more quickly than the others (see Figure 4, bottom panel). This pattern mirrored a smaller, nonsignificant trend observed in Experiment 1.

Importantly, little single-task advantage was observed when the S-Het and dual trials were compared. This suggests that the single-task benefit for auditory RTs is not related to performing the visual task per se but instead relates to costs associated with preparing for the visual stimuli. None of the trials included in this analysis actually contained the hard stimuli, so the effect cannot be directly attributed to the increased demands associated with processing the hard stimuli. Instead, the cost appears to result from the load of potentially having to engage in a visual discrimination while performing the two tasks.

The second ANOVA of the auditory RT data focused on the dual-task trials. Because the single-task trials were omitted, this analysis did not provide a means for evaluating the costs of dual-task performance. Instead, the goal was to assess the effects on the auditory task of manipulating the stimulus for the visual task. The effect of discriminability was significant,  $F(1, 6) = 30.38, p < .01, MSE = 36.64$ . Thus, in accord with the CB model, delaying response selection for the visual task did lengthen RTs on the auditory tasks. However, the magnitude of the effect was significantly smaller for the auditory task than it was for the visual task,  $t(6) = 6.24, p < .01$ , two-tailed. Whereas visual RT was slower by 57 ms for the hard discrimination, the cost on these trials was only 18 ms for the auditory task. If selection were occurring

in combined fashion for the two tasks, then delaying selection for one of the tasks should lead to a similar delay for the other task. Thus, this finding is inconsistent with the compound selection hypothesis.

To examine the dual-task cost associated with the auditory task more carefully, we divided RTs for this task on the dual-task trials into quintiles for each participant and level of discriminability. If the auditory task had to wait for selection on the visual task to be completed, then the effect of discriminability on the auditory task should have been largest for trials with the shortest auditory RTs. This is because trials with short auditory RTs are those in which response selection for the visual task is most likely to extend into the period in which preselection processes for the auditory task are complete. In fact, the pattern of costs on the auditory task in the hard visual trials was exactly the opposite: Discriminability had the smallest effect for auditory RTs in the fastest quintile and had the largest effect for auditory RTs in the slowest quintile, resulting in a significant linear trend,  $F(1, 33) = 19.54, p < .01, MSE = 110.06$ . Moreover, when the data were divided into quintiles according to speed on the visual task, the effect of discriminability on the auditory task was essentially constant across quintiles, with no significant linear trend,  $F(1, 33) < 1, MSE = 111.09$ . These patterns are inconsistent with the notion that the effect of discriminability on the auditory task resulted from a response selection bottleneck.

Identical analyses were performed on the accuracy data. In these analyses, only the effect of discriminability in the visual task was significant,  $F(1, 6) = 62.01, p < .01, MSE = 0.003$ . As expected, more errors were observed on trials with the hard discrimination. Thus, there was no evidence of any speed-accuracy trade-offs.

*Correlations.* As in Experiment 1, there were small but significant correlations between the RTs on the dual-task trials, with means of .32 ( $SD = .13$ ) for the easy discrimination trials and .24 ( $SD = .15$ ) for the hard discrimination trials. The difference in the degree of correlation for the two levels of discriminability did not achieve significance,  $t(6) = 1.81, p > .10$ .

*Interresponse intervals.* When the visual discrimination was hard, the RTs for the two tasks on dual-task trials were fairly similar: 334 ms for the visual task and 349 ms for the auditory task. In fact, the response for the visual task occurred first on only 62% of these trials. One prediction of the response selection bottleneck model is that responses should not be separated by an interval that is equivalent to the difference in the durations of the postbottleneck processes. Such an RT difference would indicate that the bottleneck processes were completed for the two tasks at the same time, which of course is contrary to the nature of a bottleneck. Therefore, the interresponse interval was tabulated for each trial by subtracting the visual RT from the auditory RT. The distribution of the interresponse intervals is shown in Figure 5. Although the distribution was mildly negatively skewed, it was clearly unimodal, and there was no evidence that any interval between the two responses was underrepresented. Thus, the difference scores provide further evidence against the idea that a CB is successively engaged by the two tasks.

In summary, Experiment 2 provides further evidence against the hypothesis that a CB constrains dual-task performance with practiced individuals. For both tasks, the S-Het trials were performed as quickly and accurately as the dual-task trials. Although the

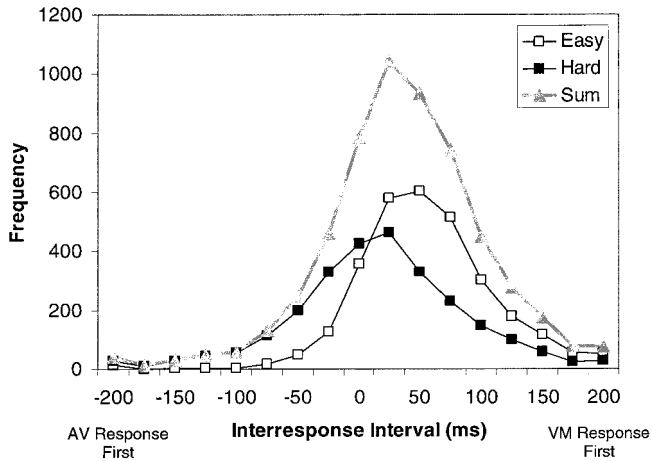


Figure 5. Distribution of intervals between the two responses on dual-task trials in Experiment 2, computed by subtracting the reaction time for the visual task (VM) from the reaction time for the auditory task (AV).

auditory task RTs were affected by the manipulation of the difficulty of the visual task, the carryover did not appear to result from a delay in initiating response selection. The dual-task cost on the auditory task was considerably smaller than that observed on the visual task, ruling out the compound selection hypothesis. Moreover, contrary to the predictions of the CB model, the carryover was smallest for the auditory trials with the fastest RTs. Such a pattern is more consistent with resource-sharing models of dual-task performance.

A resource-sharing model is also consistent with the observed increase in auditory RT on the S-Het and dual-task trials relative to the S-Hom trials. Participants are likely to have a different set when responding to single-task trials presented alone than when responding to these trials embedded in a multitask context (see Allport, Styles, & Hsieh, 1994). This change in set probably reflects allocation of resources.

### Experiment 3

Although the results from Experiment 2 were generally inconsistent with the CB model, some features of the results indicated that the two tasks were not performed entirely independently. First, for the auditory task, performance was better on the S-Hom trials than on either the S-Het or dual trials. Second, effects of the visual discriminability manipulation were observed on both tasks. Thus, the exact nature of the relationship between the two tasks merits further exploration. The data from Experiment 2 suggest that although stimulus classification processes for the visual task affected performance on the auditory task, response selection processes appeared to occur independently. Given that selection processes are generally considered the point of maximum competition for limited resources between temporally overlapping tasks, it makes sense to ask whether directly increasing the difficulty of the selection process for one task would affect performance on the other task.

Moreover, there remains another variant of the CB model that can account for the lack of substantial dual-task costs in Experiments 1 and 2. It has been proposed that central response selection

processes may not be necessary for conditions in which the S-R mapping is highly compatible (Greenwald & Shulman, 1973; Pashler, 1994a; Pashler, Carrier, & Hoffman, 1993). In our experiments, there was no obvious compatibility between the tones and the vocal responses “one,” “two,” and “three.” In contrast, a high degree of compatibility existed in the visual task, with the locations of the circles mapped to a spatially compatible arrangement of the response board. Conditions involving high S-R compatibility may represent special cases in which the response selection bottleneck is circumvented; alternatively, there may be a continuum of compatibility that progressively shortens selection processes. Perhaps the mapping used for the visual task in Experiments 1 and 2 was sufficiently compatible to minimize the bottleneck operation.

Schumacher et al. (2001) addressed this issue by combining the auditory task with a visual task involving an incompatible mapping. After six sessions, the dual-task costs combined across the two tasks averaged 78 ms. However, these costs were highly variable across the 11 participants, suggesting to the authors that different processing strategies among participants were responsible, rather than an immutable bottleneck. The experiment did not entail a direct comparison of compatible and incompatible mappings, so it was not possible to analyze the effect of the incompatible mapping in detail.

In the present experiment, we compared performance on two different S-R mappings for the visual task. Consequently, we could assess how lengthening response selection processes for one task affects performance of the other task. In particular, the inclusion of two mapping conditions allowed us to determine the degree to which increases in RTs for the manipulated task transfer to the unmanipulated task. To this end, we used the same visual stimuli as in Experiment 1, but on some blocks the S-R mapping was incompatible and on other blocks the mapping was compatible (i.e., the same as in Experiments 1 and 2). Differences in the visual task RTs for the two S-R mappings should be attributed to processes associated with response selection (Ivry et al., 1998; McCann & Johnston, 1992).

The experiment involved the same set of participants who had completed Experiments 1 and 2. The participants were first retrained under conditions identical to those of Experiment 1 to ensure that they continued to show minimal dual-task cost with the compatible mapping. At this point, we introduced the incompatible condition and counterbalanced testing with the two types of S-R mappings. In this way, we could assess the cost associated with this factor on the visual-manual task under single- and dual-task conditions and, most important, determine whether any dual-task cost was also seen on the auditory task.

### Method

*Participants.* The 7 individuals who had completed both Experiments 1 and 2 were tested in Experiment 3.

*Stimuli.* The stimuli were identical to those used in Experiment 1; the distractor stimuli for the visual task from Experiment 2 were not used.

*Procedure.* The procedure was very similar to that for the previous experiments. Participants were retrained on the basic task with the same procedures as in Experiment 1 until they met the dual-task performance

criteria.<sup>4</sup> At this point, they were transferred to the test sessions, in which they were asked to respond according to an incompatible S-R mapping on half of the blocks. The incompatible mapping was as follows: When the left-most circle appeared, participants were to press the left-most key (i.e., the S-R mapping for this stimulus remained consistent); when the center circle appeared, they were to press the right-most key; and when the right-most circle appeared, they were to press the center key. Thus, for one stimulus, the S-R mapping remained consistent; for the other two stimuli, the S-R mapping was inconsistent.

Participants completed two test sessions, each of which consisted of two halves. One half was performed with the compatible mapping, and the other was performed with the incompatible mapping. The order of the two halves was counterbalanced across participants, with each participant beginning with the compatible condition in one session and with the incompatible condition in the other session. Each half consisted of seven blocks whose order was fixed: single task (auditory), single task (visual), dual task, dual task, single task (visual), dual task, and dual task. After participants had completed this sequence of blocks, the new S-R mapping for the visual task was explained, and the sequence was repeated. Dual-task blocks consisted of 36 dual-task trials and 36 single-task trials. In the dual-task trials, 4 trials for each of the nine possible location-tone combinations were presented. Of the 36 single-task trials, 18 were performed on the visual task (6 trials for each location) and 18 on the auditory task (6 trials for each tone). The number of trials on single-task blocks was reduced to 60 (20 trials for each of the three possible stimuli for a particular task). All other details of the procedure were identical to Experiment 1.

### Results and Discussion

**Dual-task performance.** The data from the test sessions were analyzed as in Experiment 2, with the mapping factor replacing the discriminability factor. The mean RTs and accuracy rates for the four trial types and the two visual conditions are shown in the top panel of Figure 6. As is evident, there was a highly significant effect of mapping,  $F(1, 6) = 87.68, p < .01, MSE = 498.55$ , but no effect of trial type,  $F(2, 12) = 1.34, p > .20, MSE = 103.77$ , and no Mapping  $\times$  Trial-Type interaction ( $F < 1$ ). This pattern indicates that, although the hard mapping condition added 65 ms to RTs for the visual task, there was little or no dual-task cost for either the compatible or incompatible mapping trials. The participants' speed and accuracy on the two tasks were especially impressive given the potential interference between the two mappings and the participants' limited exposure to the new response assignments.

The lack of any dual-task costs for the visual task with the incompatible S-R mapping represents a failure to replicate the findings of Schumacher et al. (2001). There are a couple of potential explanations for this discrepancy. First, the visual task in the present experiment involved only three S-R pairs, whereas Schumacher et al. used four S-R pairs. Second, the present participants were considerably more practiced than those in the Schumacher et al. experiment. All of our participants had taken part in Experiments 1 and 2 and had completed at least 10 sessions with the auditory task and compatible visual S-R mapping condition before the start of Experiment 3. Moreover, they all had reached a level of proficiency on the two tasks that indicated essentially no dual-task cost with these tasks. Schumacher et al. (2001) tested naive participants in their experiment involving the incompatible condition. We expect that the additional practice led to the superior dual-task performance of our participants. Nonetheless, the current results provide strong evidence against the CB model given that the lack of a dual-task cost on the visual task was observed for all

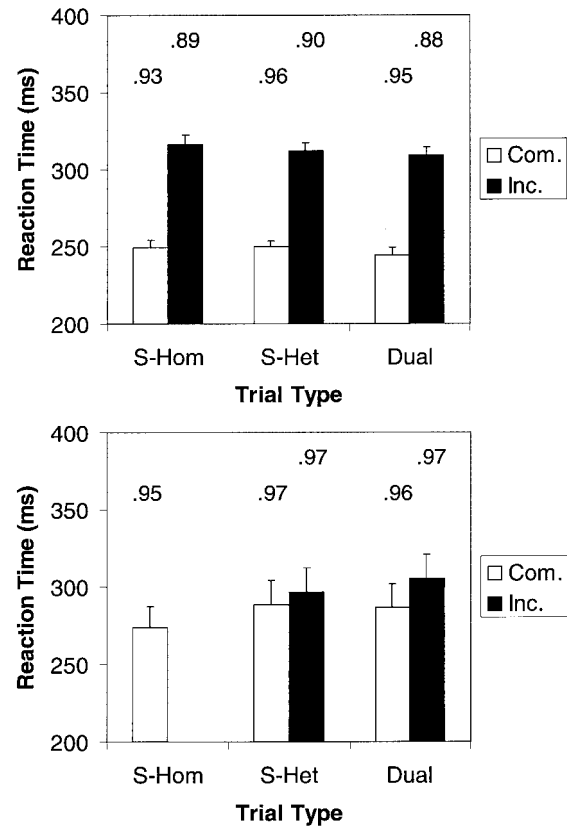


Figure 6. Mean reaction times and proportions correct for the visual task (top) and auditory task (bottom) in Experiment 3. Com. = compatible; Inc. = incompatible; S = single; Hom = homogeneous; Het = heterogeneous.

of the participants, rather than a restricted subset as in Schumacher et al.

The RT and accuracy results for the auditory task are shown in the bottom panel of Figure 6. The mapping factor was not applicable for the S-Hom blocks, so, as in Experiment 2, the data from the auditory task were examined in two separate ANOVAs. Because there could be no single-task blocks with the hard mapping for the auditory task, the ANOVA designed to evaluate dual-task performance involved only the data from the compatible mapping condition and included all three trial types. As in Experiment 2, RTs for the S-Hom trials were faster by 15 ms than RTs for the other two trial types. This was reflected by a significant effect of trial type,  $F(2, 12) = 7.96, p < .01, MSE = 55.60$ . However, there was no specific dual-task cost, as shown by the fact that mean RTs

<sup>4</sup> Of the 7 participants, 3 performed an earlier version of Experiment 3 between Experiment 2 and the version of Experiment 3 reported here. Thus, these participants had performed two sessions with the incompatible mapping approximately 5 weeks before beginning Experiment 3. In the initial version of Experiment 3, we did not include the blocks with the compatible mapping. The results were highly consistent with those reported for Experiment 3, and therefore we do not include the results of the pilot study for the sake of brevity. Inspection of the individual participants' data did not reveal any differences between those who had performed the early version and those who had not.

on the S-Het trials were within 2 ms of the mean RTs on the dual-task trials.

Unlike discriminability in Experiment 2, the mapping factor was applicable to the S-Het trials, because the S-R mapping rule for the visual task had to be maintained throughout the dual-task blocks. Thus, the ANOVA evaluating the effect of the mapping for the visual task on the auditory task involved a trial-type factor that consisted of two levels (S-Het and dual) and a mapping factor that consisted of two levels (compatible and incompatible). Both factors produced significant effects: trial type,  $F(1, 6) = 6.14, p < .05, MSE = 15.74$ , and mapping,  $F(1, 6) = 22.97, p < .01, MSE = 51.50$ . It should be noted that, as with the effect of discriminability, the magnitude of the mapping effect on the auditory task on dual-task trials (13 ms) was much smaller than the effect's magnitude on the visual task (65 ms). In addition, a significant interaction was observed between the two factors,  $F(1, 6) = 33.81, p < .01, MSE = 5.48$ . The interaction between mapping and trial type was due to the fact that the increase in auditory RTs during the blocks with incompatible visual mapping was greater on dual trials than on S-Het trials. This result is consistent with the CB model in that the effects of the lengthened selection process for the visual task should affect the auditory task much more when the visual task is actually performed. However, the difference in the mapping effect on the auditory task was fairly small (8 ms and 18 ms for S-Het and dual, respectively) in comparison with the consistent effect (62 and 65 ms) on the visual task. This difference makes straightforward CB model accounts of the interaction implausible.

In PRP experiments, manipulations of S-R mapping for the task that is performed first typically produce equivalent costs for both tasks at short SOAs. Thus, if we assume that the responses for the visual task are selected before the responses for the auditory task, the present results represent a departure from those observed in the PRP paradigm. The proposal that the absence of dual-task costs is caused by this sort of sequential arrangement of selection processes predicts that the costs should be nearly equivalent for the two tasks because the auditory task must wait for the completion of the visual task. However, the smaller cost for the auditory task could result from that task being performed first on some percentage of the trials. Presumably, trials on which selection for the auditory task is performed first will have shorter RTs, and no transfer of the mapping effect from the visual task will be in evidence.

To examine this possibility, we divided RTs for the two trial types within each level of mapping into quintiles and subtracted quintiles for the incompatible mapping from corresponding quintiles for the compatible mapping. The faster quintiles did show smaller effects of mapping, and this linear trend was significant for the dual trials (fastest quintile: 16-ms cost; slowest quintile: 26-ms cost),  $F(1, 33) = 4.58, p < .05, MSE = 83.88$ . This pattern was not observed in the S-Het trials (fastest quintile: 10 ms; slowest quintile: 6 ms). Importantly, the magnitude of the effect was insufficient to explain the difference between the costs for the visual and auditory tasks. Moreover, a similar trend was observed in Experiment 2 when the CB model predicted the opposite pattern. Thus, a resource-sharing model appears to provide a better account of the small dual-task costs.

Ruthruff, Johnston, & Van Selst (2001) have argued that, with extensive practice, computations that initially occur during the bottleneck stage can be shifted to occur before the bottleneck. In

this light, it is useful to consider whether the smaller mapping costs for the auditory task could reflect the operation of a late bottleneck. A late bottleneck would permit much of the additional processing required for the hard mapping to occur in parallel with prebottleneck stages for the auditory task. However, if it is assumed that the response for the auditory task is selected after the response for the visual task, the cost of slowing the visual task should transfer entirely to the auditory task. In other words, the late bottleneck explanation can account for reduced effects on the manipulated task itself but not for reduced effects on the other task.

Identical ANOVAs were performed on the accuracy data. For the visual task, only the effect of mapping was significant,  $F(1, 6) = 24.94, p < .01, MSE = 0.001$ , indicating that participants were more accurate on the compatible mapping blocks (99%) than the incompatible mapping blocks (86%). For the auditory task, the effect of trial type was significant,  $F(2, 12) = 4.90, p < .05, MSE = 0.0002$ , reflecting the fact that accuracy was lowest for the S-Hom trials (95%) and highest for the S-Het trials (97%). A paired  $t$  test conducted on the accuracy data for the S-Het and Dual trials revealed no significant effect,  $t(6) = 1.67, p > .10$ .

*Correlations.* Increasing the difficulty of the S-R mapping had little effect on the correlations between the RTs for the two tasks, which remained quite low ( $M = .22, SD = .16$ ). A  $t$  test performed on the correlations for the two mappings revealed no significant effect.

Experiment 3 provides strong evidence against the CB model. Even when a difficult, incompatible S-R mapping was introduced for the visual task, we failed to find any evidence of a dual-task cost on that task. The manipulation was highly effective in slowing RTs on the visual task, but the magnitude of this cost was similar on single- and dual-task trials. The lack of a dual-task cost is especially impressive considering that the participants had little practice with the incompatible mapping before the first test session. Whatever participants had learned to enable them to perform the two selection processes simultaneously in Experiments 1 and 2, it transferred successfully to conditions in which the S-R mapping for one task was changed.

As noted earlier, the CB model could account for the lack of a dual-task cost if the visual task was consistently performed first. However, there was no difference between the S-Het and dual-task trials for the auditory task when participants performed the easy visual mapping, and there was only a 10-ms difference when they performed the hard mapping. Because the mapping is assumed to affect bottleneck processes,<sup>5</sup> it is difficult for CB models to account for the dramatically smaller cost of the visual mapping on the auditory task given the large costs associated with the mapping manipulation on the visual RTs.

In summary, Experiments 2 and 3 provide strong evidence that response selection for the auditory and visual tasks is performed in an overlapping fashion. Manipulations of bottleneck and prebottleneck processes for the visual task produced minimal costs on the auditory task. These results indicate that, with extensive practice, people are able to perform two concurrent tasks independently, with no indication of a shared processing stage such as that postulated by the CB model.

<sup>5</sup> Note that even if mapping costs were attributed to prebottleneck processes, the costs for the two tasks should be equivalent.

## Experiment 4

The results from Experiments 1–3 were remarkably incompatible with CB models. How are we to reconcile these results with the extensive body of research indicating robust interference between two temporally overlapping tasks? One obvious factor is practice: Cost-free dual-task performance was evident only after moderate practice with the visual–manual and auditory–vocal tasks, even if the benefits of this practice generalized to novel stimulus pairings (Experiment 1), more difficult stimulus discriminability (Experiment 2), and novel S-R mappings (Experiment 3).

A second factor is that in most dual-task studies, especially those involving the analytic power of the PRP method, the stimuli for the two tasks are presented sequentially. Perhaps dual-task performance was achieved in the present experiments because the SOA was zero, or because it was constant. That is, when the relative onset of the stimuli is completely predictable, participants may be able to precisely schedule different components of the two tasks to avoid conflict between bottleneck processes. A variant of this proposal is that the constant SOA allows participants to treat the two tasks as a single one during certain critical stages of processing. According to this account, some portion of the selection process is synchronized for the two tasks so that no delays occur as the result of a queuing procedure.

A strategy involving the synchronization of selection processes should be disrupted when the relative onset of the stimuli is irregular. To evaluate this hypothesis, we introduced an SOA between the stimuli for the two tasks in Experiment 4. If dual-task performance is contingent on the predictability of the onsets of the stimuli, this manipulation should produce dual-task costs. On one third of the dual-task trials, the auditory stimulus was presented 50 ms before the visual stimulus; on another third, the visual stimulus was presented 50 ms before the auditory stimulus. On the remaining third, the two stimuli were presented simultaneously, as in the previous experiments. This manipulation effectively produced a 100-ms range in the relative onset of the two stimuli. Given the results from PRP studies, this range should be sufficient to produce very discernible effects on processes relying on precise scheduling to accomplish the observed levels of dual-task performance.

The mapping manipulation used in Experiment 3 was retained in this experiment for two reasons. First, it provided a further test of carryover effects between the two tasks. In Experiments 2 and 3, we assumed that response selection for the visual task had to be occurring first because, under compatible conditions, this task was about 50 ms faster than the auditory task. Although unlikely, it is possible that selection for the auditory task occurred first but that the responses were slower because of differences in postselection processes. If selection occurred first for the auditory task, then manipulations of the visual task would have little effect on the auditory task. By giving the visual task a head start of 50 ms on one third of the trials in Experiment 4, we should observe greater overlap between the two selection processes and, therefore, greater effects of the mapping manipulation on the auditory task.

Second, there was the concern that selection processes are minimally required for the visual task when the compatible mapping is used. Moving the onset of the visual stimulus would have little effect on performance if selection were nearly automatic. The 50-ms compatibility effect in Experiment 3 provides strong evidence that selection processes are not negligible for these trials.

Thus, retaining the incompatible mapping condition is critical for testing selection overlap.

Along these lines, one might suppose that selection for the auditory task is occurring considerably later than selection for the visual task. This hypothesis is in accord with the lack of dual-task costs in Experiment 1 as well as the small costs observed for the auditory task produced by manipulations to the visual task. That is, if selection for the auditory task were occurring, on average, 35 ms after completion of selection for the visual task, then delaying or extending selection for the visual task by 50 ms would produce only a 15-ms cost on the auditory task. This prediction matches the observed pattern of data for Experiments 2 and 3. However, if the auditory task has a 50-ms head start, then there should be greater potential for overlap, resulting in larger dual-task costs. Similarly, if selection were occurring first for the auditory task, presenting the visual stimulus 50 ms before the auditory stimulus should lead to dramatic interference.

Choosing a 50-ms SOA had some important advantages in the present context. First, it is commonly used in PRP experiments, allowing ready comparisons between this experiment and others in which it has been shown to generate large dual-task interference effects. Second, the 50-ms duration approximates the size of the effects observed in Experiments 2 and 3. Thus, we can compare the effects of delays that are induced by additional processing with the effects of delays that result from the stimulus onsets. If the small dual-task costs observed in the preceding experiments occurred because of general resource limitations, then the SOA manipulation should have no effect on participants' ability to perform the two tasks. Alternatively, if the dual-task costs result from scheduling problems, then the SOA manipulation should produce effects similar to those observed with the manipulations of discriminability and mapping. Finally, but critically, 50 ms is sufficiently short that it is unlikely that participants will notice the manipulation and consciously adopt alternative strategies to accommodate it. Indeed, we avoided longer SOAs because we expected that they would induce participants to adopt a strategy of responding to the two stimuli sequentially (Schumacher et al., 2001).

We continued testing the same set of participants. Our focus was on examining the hypothesis that these highly trained individuals achieved near-perfect dual-task performance by learning to precisely schedule how the two tasks engage a CB. If this hypothesis is correct, then our subtle disruption of the timing between the two tasks should reveal dual-task costs. Alternatively, if these participants are performing the two tasks independently, then the manipulation of the relative timing for the two tasks should have minimal effect.

## Method

*Participants.* The 7 individuals who had participated in Experiments 1–3 were tested in Experiment 4.

*Stimuli.* The stimuli were identical to those used in Experiment 3 except that, on dual-task trials, the visual and auditory stimuli were not always presented simultaneously.

*Procedure.* We did not inform the participants of any difference between Experiments 3 and 4. Rather, we allowed them to believe they were performing a continuation of Experiment 3. Unbeknownst to the participants, an SOA was introduced on two thirds of the trials. Each dual-task block consisted of 54 dual-task trials and 36 S-Het trials. On 18 of the

dual-task trials, the auditory stimulus was presented 50 ms before the visual stimulus, and on 18 other dual-task trials, the visual stimulus was presented 50 ms before the auditory stimulus. On the remaining 18 dual-task trials, presentation of the stimuli was simultaneous, as in the previous experiments. After completing the test sessions, participants were interviewed to determine whether they had noticed that, on some trials, one of the stimuli appeared before the other. None of the participants reported being aware of the SOA manipulation.

### Results and Discussion

Figure 7 presents the latency and accuracy data for the visual (top panel) and auditory (bottom panel) tasks. For the dual-task trials, the results are shown separately for the conditions in which the auditory stimulus was presented first (A), the visual stimulus was presented first (V), or the two occurred simultaneously (S).

**Dual-task performance.** Considering first the visual task data, two separate ANOVAs were tested. The first ANOVA, designed to evaluate dual-task performance, excluded the data from the SOA conditions in which the stimuli were not presented simultaneously. These data allowed us to evaluate whether the results of Experi-

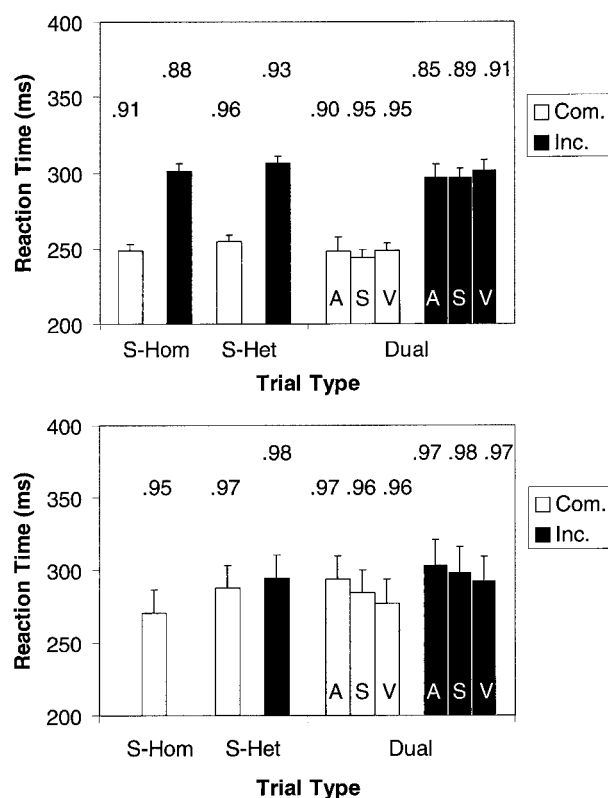


Figure 7. Mean reaction times for the visual task (top) and auditory task (bottom) in Experiment 4. For the dual-task trials, the data are divided in terms of stimulus onset asynchrony. Reaction times from trials in which the stimulus for the auditory task was presented 50 ms before the stimulus for the visual task are labeled with an A, reaction times from trials in which the stimuli appeared simultaneously are labeled with an S, and reaction times from trials in which the stimulus for the visual task appeared 50 ms before the stimulus for the auditory task are labeled with a V. Com. = compatible; Inc. = incompatible; S = single; Hom = homogeneous; Het = heterogeneous.

ment 3 would replicate when the SOA was no longer constant. This analysis involved a mapping factor (compatible or incompatible) and a trial-type factor (S-Hom, S-Het, or dual). The compatible mapping trials were performed 52 ms more quickly than the incompatible mapping trials,  $F(1, 6) = 152.42, p < .01, MSE = 190.05$ , but neither the effect of trial type nor the Mapping  $\times$  Trial-Type interaction approached significance ( $F_s < 1$ ). In short, there appears to have been little cost of performing the two tasks simultaneously for the 0-ms SOA trials, replicating the results of Experiment 3.

The second ANOVA focused on the effects of the SOA manipulation and eliminated the data from the single-task trials. Thus, two factors were included: mapping (compatible vs. incompatible) and SOA (auditory stimulus first, simultaneous, or visual stimulus first). As in the first ANOVA, only the effect of mapping was significant,  $F(1, 6) = 136.47, p < .01, MSE = 210.10$ . The effect of SOA did not approach significance ( $F < 1$ ), suggesting that the relative onsets of the two stimuli had little effect on performance of the visual task.

To evaluate dual-task performance on the auditory task, we submitted the data from the compatible mapping condition, excluding those trials on which the stimuli were not presented simultaneously, to a one-way ANOVA with a three-level (S-Hom, S-Het, or dual) trial-type factor. S-Hom trials were performed more quickly than the other trial types,  $F(2, 12) = 12.33, p < .01, MSE = 49.84$ . However, the more direct comparison between the S-Het (288 ms) and dual-task (284 ms) trials failed to show a dual-task cost. This pattern is consistent with what was observed in the previous experiments and suggests that the advantage for the S-Hom (270 ms) trials may result from subtle changes in participants' strategies between the single- and dual-task blocks.

A second ANOVA was performed on the auditory RTs from the dual-task trials to evaluate the effects of the visual task mapping and SOA manipulations. The auditory task was performed 15 ms more quickly when the visual task involved the compatible mapping than when the visual task involved the incompatible mapping,  $F(1, 6) = 38.60, p < .01, MSE = 47.33$ , closely replicating the findings of Experiment 3. The effect of SOA,  $F(2, 12) = 20.89, p < .01, MSE = 30.54$ , is shown in the bottom panel of Figure 7. On average, auditory RTs were 14 ms faster when the visual stimulus appeared first than when the auditory stimulus appeared first, with the RTs on the simultaneous trials falling between the two staggered conditions. This result effectively rules out the possibility that selection for the auditory task occurs well after selection for the visual task. Had this been the case, the opposite pattern of costs would have been observed. Rather, the data suggest that the visual signals may have had a facilitatory effect on auditory RTs. The Mapping  $\times$  SOA interaction did not achieve significance,  $F(2, 12) = 2.79, p > .10, MSE = 10.56$ .

These results are difficult to accommodate with models that involve a response selection bottleneck. The lack of an interaction between the mapping and SOA manipulations argues against mixture models in which, when the stimuli are presented simultaneously, response selection sometimes occurs first for one task and sometimes occurs first for the other. We would expect the 50-ms handicap to have a large effect on these proportions and to consequently produce systematic changes in the pattern of dual-task costs. Instead, the effects of SOA were small and in the opposite direction, and the effects of the mapping manipulation were largely

restricted to the visual task. As mentioned earlier, the effect of mapping can best be accounted for by resource-sharing models of dual-task performance.

Identical ANOVAs were performed on the accuracy data. For the auditory task, there were no significant effects. For the visual task, the compatible mapping blocks were performed with greater accuracy than the incompatible mapping blocks (.93 vs. .89),  $F(1, 6) = 21.53, p < .01, MSE = 0.002$ , and the S-Het (.94) trials were performed with greater accuracy than the S-Hom (.90) and dual (.91) trials,  $F(2, 12) = 6.77, p < .05, MSE = 0.001$ . The SOA ANOVA showed that the dual-task trials in which the auditory stimulus was presented first were performed less accurately than the other dual-task trials (.88, .92, and .93 for auditory first, simultaneous, and visual first, respectively, averaged across the two mappings),  $F(2, 12) = 9.08, p < .01, MSE = 0.001$ . This latter effect indicates that, contrary to the findings from the RT analyses, the visual task was sensitive to the SOA manipulation. That accuracy was worse when the auditory stimulus appeared first is consistent with the proposition that critical processes were executed for the visual task before the auditory task. Note also that the pattern is consistent with the effect observed in the auditory RTs; both indicate that performance was better when the auditory stimulus was delayed. However, the magnitude of the effect was small, and there were no corresponding effects for the visual task RTs (the means were within 4 ms for the three SOAs).

**Correlations.** The correlations between the RTs for the visual and auditory tasks were smaller than those observed in the previous experiments, with a mean of .15. A two-way ANOVA on the correlations between the RTs for the two tasks with mapping and SOA as factors revealed a significant effect of SOA,  $F(2, 12) = 8.24, p < .01, MSE = 0.021$ . When the auditory stimulus was presented first, the correlation was near zero ( $M = .03, SD = .16$ ). In contrast, the correlations for the simultaneous ( $M = .20, SD = .18$ ) and visual stimulus first ( $M = .24, SD = .10$ ) trials were more in line with those observed in the previous experiments. This finding is interesting in that it suggests that the correlations observed in the previous experiments did not result from a general variation of factors such as motivation and alertness from trial to trial. If this were the source of the correlations, they should not be mediated by SOA.

The difference in the correlations as a function of SOA is puzzling. The results suggest that there was greater synchronization between the two tasks as the auditory task was delayed relative to the visual task. The RTs for the auditory task and the accuracies for the visual task both indicate that presenting the auditory stimulus first increased the difficulty of performing the dual-task trials. That the correlation decreased as the dual-task combination became more difficult is inconsistent with CB models and suggests that the difficulty does not result from greater overlap of central operations. It is possible that the pattern of correlations reflects a goal to minimize the time between the two responses. In other words, participants may essentially use the visual response as a temporal marker for when the auditory response should occur. When the response for the auditory task is produced before the visual response, this constraint is removed, presumably eliminating the correlation.

In addition to making predictions about the correlations between RTs for the two tasks, the CB model imposes limits on the intervals that can exist between the two responses. Because selec-

tion processes for the two tasks cannot be completed at the same time, the responses should not be separated by a duration equivalent to the difference in the two postselection processes. The combination of different SOAs and S-R mappings in Experiment 4 offered an excellent opportunity to test this hypothesis. For example, when the compatible mapping was used and the visual stimulus appeared before the auditory stimulus, the visual response was produced approximately 80 ms before the auditory response. In contrast, when the incompatible mapping was used and the auditory stimulus occurred before the visual stimulus, the visual response was produced 44 ms after the auditory response. The distributions of interresponse intervals are plotted as a function of mapping and SOA in Figure 8. As can be seen, the set of distributions spanned approximately 150 ms, and there was little evidence of gaps. This uniformity is difficult to account for with CB models. Moreover, if participants had learned to respond in a particular order during the previous experiments (e.g., respond to the visual stimulus first), they were able to abandon this strategy without slowing their performance when the task demands were altered.

In summary, the results of Experiment 4 are largely consistent with the previous experiments, but they also contribute some intriguing qualifications. The effects of SOA demonstrate that the two tasks are not performed completely independently: Performance on each task is influenced by the relative timing of the two tasks, although the effects are rather subtle. Importantly, unlike variables such as perceptual discriminability and S-R mapping, the SOA manipulation does not increase processing demands. It seems unlikely that the effect of SOA on auditory RT can be accounted for in terms of deliberate resource allocation strategies, a point emphasized by the fact that the participants appeared to be unaware of the SOA variations.

Although it is important to identify the sources of interference in these studies, we do not wish to lose sight of the most impressive aspect of the data. Namely, SOA, as well as our previous manipulations (discrimination and mapping difficulty), had relatively

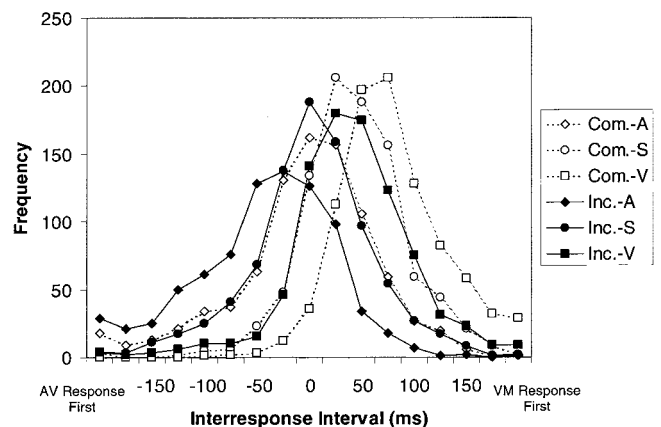


Figure 8. Distribution of intervals between the two responses on dual-task trials in Experiment 4, computed by subtracting the reaction time for the visual task from the reaction time for the auditory task and then adding the stimulus onset asynchrony. Com. = compatible; A = auditory stimulus presented first; S = simultaneous presentation; V = visual stimulus presented first; Inc. = incompatible; AV = auditory; VM = visual.

small effects on dual-task performance. The two tasks appear to be performed nearly independently. In the case of the visual task, the mean RTs for all conditions within each of the mapping levels were within 12 ms of each other. In the case of the auditory task, the RTs were within 34 ms of each other. Thus, although interactions between the two tasks could be observed, performance was only minimally impaired on dual-task trials. The interference effects did not follow predictions derived from models postulating a response selection bottleneck. Rather, it appears that, under the current conditions, participants were selecting the responses for the two tasks in parallel, an operation that is eschewed in many dual-task settings.

### General Discussion

The experiments described here provide a detailed look at dual-task performance among practiced individuals. Most of the earlier work on this issue focused on relatively crude measures of performance (e.g., Spelke et al., 1976) or involved a standard PRP paradigm in which the use of a variable SOA may favor a strategy in which the two tasks are responded to in a successive manner (e.g., Ruthruff, Johnston, & Van Selst, 2001; Van Selst et al., 1999). Inspired by the recent report of Schumacher et al. (2001), we used a method in which the stimuli for a visual-manual task and an auditory-vocal task were presented simultaneously and performance-based rewards were designed to encourage participants to give equal (and high) priority to both tasks. Similar to the findings of Schumacher et al., participants in the current studies were quite capable of performing two distinct tasks simultaneously and could do so with little degradation in performance relative to when either task was performed alone. Moreover, the dual-task proficiency of our participants was extremely robust, persisting over a variety of task manipulations. It appears that, with moderate practice, the two tasks were essentially performed independently.

These results present a serious challenge to models of dual-task performance that postulate a unitary CB associated with response selection that persists throughout practice. The present experiments were designed to examine ways in which CB models might account for near-perfect dual-task performance. One hypothesis is based on the idea that, with extensive practice, people reconfigure the two tasks into a single compound entity. By this view, the lack of dual-task interference results from the integration of the stimulus pairs such that a compound response results from the operation of a unitary response selection process. The combined selection hypothesis is untenable, however, for at least two reasons. First, we did not observe any significant differences between unpracticed stimulus combinations and practiced combinations. Second, delaying response selection for one task had only small effects on RTs for the other task.

The second hypothesis is based on considerations of the time course of the component operations required to perform the two tasks. We assume that the primary benefit of practice is to shorten the time required for response selection (Ruthruff, Johnston, & Van Selst, 2001). If so, then absence of dual-task interference could result when there is no temporal overlap between the two tasks in terms of their demands on a response selection process. That is, because of differences in the time required for upstream operations, the tasks end up engaging the response selection process sequentially.

This hypothesis seems implausible given the various manipulations we used in Experiments 2–4. Delaying (Experiments 2 and 4) or lengthening (Experiments 3 and 4) the selection process for the visual task produced only small effects on the auditory task. We would expect that these manipulations should have created conditions of overlap if response selection tended to occur first for the visual task. It is logically possible that response selection occurred first for the auditory task. However, the RTs for the auditory task were consistently slower than the visual-manual RTs in the compatible mapping conditions and approximately equal for the difficult perceptual discrimination and mapping conditions. Moreover, in Experiment 4, we failed to find evidence of a dual-task cost when either task was given a 50-ms head start. SOA had almost no impact on visual-manual RTs and only a small impact on auditory-vocal RTs, even when the selection processes for the visual task were lengthened by the incompatible mapping. Considered together, it is highly unlikely that the selection processes could have been misaligned in all of the conditions of Experiments 2–4.

### *Is the Lack of Interference Due to a Short Bottleneck Stage?*

Nonetheless, the logic of our experiments is predicated on the assumption that the bottleneck stage associated with CB models comprises a significant proportion of the RT interval. Therefore, it is reasonable to ask how long a bottleneck stage could last while remaining essentially undetected in our experiments. The answer to this question is complex. It is contingent on assumptions made about the various processing operations involved in these tasks, including the durations of the nonbottleneck processes, their variances, and whether there are multiple bottlenecks.

In an attempt to shed some light on this question, we developed a computer simulation to exhaustively search the range of possible bottleneck durations given our experimental observations and, for each duration, compute expected dual-task costs. For brevity, we focus on the easy mapping condition of Experiment 4 because it provides the most stringent constraints on CB models. This condition produced short RTs, limiting the range of stage durations for the two tasks. Moreover, the RTs at all three SOAs were similar to the S-Het condition, indicating that if bottleneck stages were operative, their overlap was minimal across a range of relative stage onsets.

Our model made some basic assumptions about the nature of the bottleneck. First, as is traditional, the tasks were divided into three stages: a prebottleneck stage (Stage A), a bottleneck stage (Stage B), and a postbottleneck stage (Stage C). The sum of the durations of these stages was, by definition, the RT for that task. Some research has suggested that there may be multiple bottlenecks (e.g., De Jong, 1993), and splitting the bottleneck into distinct subcomponents is one way to potentially minimize interference. However, such models have greater degrees of freedom and produce much more complex patterns of behavior. Because we wanted to determine the temporal extent of a unitary bottleneck stage that would have been undetected in our experiments, we opted to investigate the more straightforward three-stage model.

Second, it was assumed that once the bottleneck stage for a task had begun, the bottleneck was occupied until that stage was complete. That is, once Stage B had begun for one of the tasks,

Stage B for the other could not begin until the first was complete. This assumption, of course, captures the essential notion of a bottleneck. It is important to note that we did allow the bottleneck stage to be of a different duration for the two tasks. For example, response selection for the visual–manual task could be shorter than that for the auditory–vocal task. Third, we assumed that whichever task completed Stage A first would automatically occupy the bottleneck first. If the two tasks were ready to begin their respective bottleneck stages simultaneously, the task with the shorter bottleneck stage would go first.

We set minimum durations for the nonbottleneck stages at 80 ms. Therefore, for both tasks, the bottleneck stages could not begin until at least 80 ms after the onset of the stimulus and had to end at least 80 ms before the response. This constraint is admittedly arbitrary but seems reasonable given the time required for stimulus processing–identification and response implementation. It was also assumed that the durations of all of the stages were constant, with zero variance. Although this assumption is clearly unrealistic, it is unlikely to produce inflated measures of interference. Shorter than average stage durations can potentially alleviate interference; by the same token, however, longer than average durations are likely to increase interference. Furthermore, stages with no variance can be scheduled more efficiently, because there is no uncertainty regarding when critical operations will be complete.

Finally, to estimate the longest possible Stage B durations, we had to select a maximum amount of allowable interference. For the easy visual stimuli in Experiment 4, the maximum upper bound of the 90% confidence intervals for the combined dual-task costs across the three SOAs was 10 ms. Thus, the total delay for both tasks arising from one Stage B waiting for the completion of the other Stage B was not permitted to be more than 10 ms.

With these assumptions, many degrees of freedom remain. For a given set of durations of the four nonbottleneck stages, multiple combinations of durations of the two B stages are possible. Thus, to simplify the search, the duration of one of the B stages was held constant, and the model determined the maximum duration of the remaining stage. In some cases, depending on the durations of the nonbottleneck stages, the durations of the two bottlenecks are fungible, so time can be transferred from the bottleneck stage of one task to the other without changing the amount of interference. However, because the mean RTs for the two tasks differ, the total amount of bottleneck time is often longer if the bottleneck stage for the auditory task occurs second.

Preliminary runs of the simulation indicated that if either bottleneck were longer than 60 ms, then essentially no combination of the stage durations would produce interference that was less than the length of the shorter bottleneck. We therefore tested how long the bottleneck process of the auditory task could be, assuming that the bottleneck process for the visual task was 30 ms, and how long the visual task's bottleneck process could be, assuming that the auditory task's bottleneck process was 30 ms. The results of this simulation are shown in Figure 9. The *x*-axis and *y*-axis indicate various combinations of Stage A durations for the auditory and visual tasks. Three levels of shading are used to indicate the maximum duration for the bottleneck operation for one task given a 30-ms bottleneck duration for the other task (visual task fixed in the top panel and auditory task fixed in the bottom panel).

As can be seen, bottleneck stages lasting between 20 and 40 ms are possible across a range of Stage A combinations. Less likely

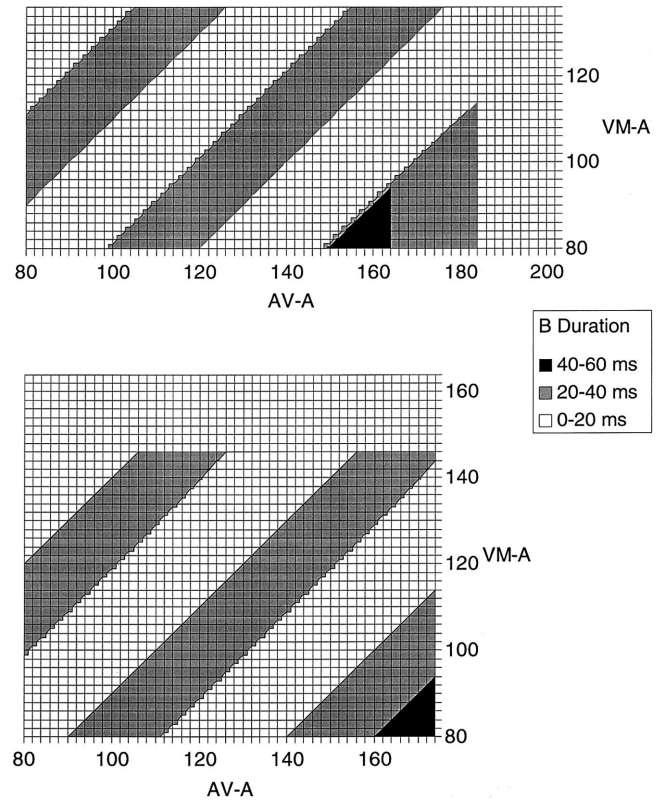


Figure 9. Maximum durations of bottleneck stages that could have gone undetected in the easy mapping condition of Experiment 4. The *x*-axis represents a range of values for the duration of the prebottleneck stage (Stage A) for the auditory–vocal task. The *y*-axis represents a range of values for Stage A for the visual–manual task. Top: Possible durations for the auditory–vocal task bottleneck stage (Stage B), assuming that this stage lasts 30 ms for the visual–manual task. Bottom: Possible durations for the visual–manual task bottleneck stage (Stage B), assuming that this bottleneck stage lasts 30 ms for the auditory–vocal task. Maximum bottleneck durations less than 20 ms are shown in white, those between 20 and 40 ms are shown in gray, and those between 40 and 60 ms are shown in black. VM = visual; AV = auditory.

but still possible are bottleneck durations of 40–60 ms. These results indicate that, even with the small dual-task costs observed in our studies, a CB model may still be viable if it is assumed that the duration of the bottlenecks represents only a small proportion of the RT period. The simulation also makes explicit the idea that the benefits of practice are probably focused on the processing operations typically associated with the bottleneck, the mapping of a stimulus to its response (e.g., Shiffrin & Schneider, 1977; Van Selst et al., 1999).

Nonetheless, the results of our experiments seem at odds with many of the solutions shaded in Figure 9. Consider solutions in which the Stage A durations are roughly equal. For example, if the bottleneck stages for both tasks last 30 ms, and the A stages for the auditory and visual tasks are 100 ms and 130 ms, respectively, then overlap for the two bottleneck stages is observed only when the visual stimulus precedes the auditory stimulus by 50 ms. In this case, there should be a 10-ms delay on the auditory task. In fact, the data reveal the opposite: The RT on the auditory task is slower

when the tone is presented before the visual stimulus. Indeed, many of the combinations producing acceptable dual-task cost fail to predict the direction of this cost.

Next, consider solutions in which the two tasks have very different Stage A durations. The observed change in auditory RT as a function of SOA is found only for combinations in which Stage A is much longer for the auditory task than for the visual task. For example, if Stage A were 100 ms for the visual task and 170 ms for the auditory task, then two 30-ms bottleneck stages would overlap only for the tone-first SOA, and here the auditory response would be delayed 10 ms. Combinations involving very different Stage A durations compose the dark regions, those representing combinations allowing for the longest possible bottleneck duration.

In interpreting these results, it is important to bear in mind that the model represents the idealized scheduling of stages. The transitions between stages were assumed to be instantaneous, and the maximum allowable delays were slightly larger than what was observed in any of the experimental conditions. Thus, the values represent an upper limit on the bottleneck stage durations. Moreover, the bottleneck stages abut each other for at least one of the three SOAs. Therefore, any lengthening of either Stage A or Stage B for the task first requiring the bottleneck would necessarily be passed on to the other task. Not only would such carryover result in larger dual-task costs, but it would also lead to correlations between the RTs for the two tasks. Although significant correlations were observed, they were much weaker than those reported with unpracticed participants and a standard PRP paradigm (e.g., Pashler, 1989).

Further constraints for possible stage configurations can be gleaned from the incompatible mapping condition of Experiment 4. Here the RTs increased by 52 and 13 ms for the visual and auditory tasks, respectively. The increases in the visual task RTs would traditionally be considered to reflect increases in the bottleneck stage, because only the S-R mapping changed. However, if the bottleneck stage for the visual task is 80 ms long (30 ms + 50 ms), there is no room for any bottleneck process for the auditory task except when Stage A is greater than 130 ms for the visual task and less than 90 ms for the auditory task. Even here, the duration of the bottleneck stage for the auditory task would have to be less than 20 ms.

This example makes clear an important result of the simulations. When either bottleneck extends beyond 30 ms, the viability of a CB model becomes greatly reduced. Nonetheless, the simulations also underscore the difficulty of definitively eliminating CB models. If practice reduces the duration of the bottleneck operation to very short values, then it might be hard to detect the presence of such operations, at least if one uses a limited range of SOAs and the variances of Stages A and B are minimal. However, for such bottleneck stages to exist, the processing stages would have to be precisely timed so as to just miss interfering with each other at all three SOAs, an unlikely proposition.

### *Is the Lack of Interference Due to the Bottleneck Stage Being Bypassed?*

It should be borne in mind that CB models predict interference between the two tasks only when both require bottleneck processes (see Greenwald & Shulman, 1973). In this regard, note that the

difficulty of the auditory task was not manipulated in any of the present experiments. This raises the possibility that, after extensive practice, performance on the auditory task can bypass a CB associated with response selection. Such a hypothesis would be consistent with the failure to find strong evidence of dual-task interference in Experiments 1–4. In support of this hypothesis, previous work has shown negligible dual-task cost on a visual-spatial tracking task when the secondary task involves shadowing (MacLeod & Posner, 1984). However, shadowing involves a much more compatible mapping between the stimulus and response than in our studies and has been thought to engage a “privileged” loop.

Both theoretical and empirical considerations raise problems for the hypothesis that the auditory task engaged a specialized response selection mechanism in our experiments. First, the mapping between the tones and vocal responses was arbitrary, so it seems unlikely that response selection here would bypass a general response selection module, should one exist. Second, the RTs on the auditory task continued to decrease across the four experiments: Considering the performance on the S-Het trials of the 7 participants who completed all of the experiments, the mean RT for the auditory task during the easy mapping at the end of Experiment 4 was 38 ms faster than at the end of Experiment 1. A similar improvement was evident on the dual-task trials. As noted earlier, improvements from extended practice most likely come from processing stages associated with response selection (see Van Selst et al., 1999).

A related account of the data proposes that dual-task interference diminishes as one or both of the tasks become automatized.<sup>6</sup> That is, extensive practice may allow for the formation of direct associations between stimuli and responses, obviating the need for the response selection bottleneck (see Logan, 1988). Given the considerable controversy surrounding the precise meaning of the term *automaticity*, we wish to be cautious before relying on its explanatory power for the present data. To the extent that the term is used to refer to the bypassing of response selection processes, such an account is clearly compatible with our findings. The present design did not allow us to determine whether one or both tasks became automatized in this sense.

However, it seems that an automaticity-based account borders on circularity: Dual-task performance without interference implies that (at least) one task has become automatized; if a task is automatized, then there is no interference during dual-task performance. We believe that the current results demonstrate a more principled way to operationalize automaticity: Performance on a task can be said to be automatized if it is unaffected by the inclusion of a second task. But this notion of automaticity adds little explanatory value. Moreover, automaticity may be limited to a particular context. For example, the introduction of a second auditory task might have produced extensive interference in our auditory-vocal task even with our practiced participants.

### *Implications for the Study of Multitask Performance*

Given the large body of work showing robust interference effects elegantly characterized by the response selection bottleneck model, our results were quite unexpected. Not only do they appear

<sup>6</sup> We thank Hal Pashler for this suggestion.

to rule out the sequential operation of a shared response selection process, but they also argue against the proposal that the selection processes are somehow synchronized. Why should simultaneous presentation paradigms provide such a dramatically different pattern of results than had been found in previous studies of concurrent task performance? Schumacher et al. (2001) examined this question by having their trained participants complete a final test session in which a series of variable SOAs was introduced with the auditory stimulus always presented in advance of the visual stimulus. Moreover, the instructions were altered to emphasize that priority should be given to the auditory task. Under these conditions, a classic PRP effect was observed: RTs for the auditory task were constant across SOAs, and RTs for the visual task were negatively correlated with SOA. Because these same participants had shown good dual-task performance in the previous experiment, the authors argued that the PRP effect does not result from an immutable response selection bottleneck. Instead, they suggested that the RTs observed were the product of a strategy used to prevent the response for Task 2 from preceding the response for Task 1.

The SOA manipulation we used in Experiment 4 provided a useful general test of whether PRP-like effects result from structural limitations or strategic factors. Unlike the traditional PRP paradigm, participants were unaware of the variation of the SOA and thus did not consciously schedule task operations differently. Although applicable across a fairly limited range of SOAs, our results indicate that such manipulations of SOA can be successfully used to vary the relative onsets of stimuli by at least 100 ms, a range within which traditional PRP studies have revealed pronounced dual-task costs. With our manipulation, the dual-task costs were minimal. It is important to note that, in traditional designs, participants are informed of the variation in the SOA and thus may attempt to adjust control processes on the basis of its perceived length. With the hidden manipulation of SOA, the effects of SOA can be observed without strategic influence.

Although the current results are at odds with the CB model, it is also apparent that we did not find complete independence in the performance of the two tasks. In Experiments 2–4, we consistently observed small increases in auditory RT when the visual task became more difficult. These observations can be accounted for by general resource sharing; when the visual task is hard, fewer resources are available for processing the auditory task, leading to slower RTs. The carryover effects are also consistent with the idea that the scheduling of processes for one task is affected by the timing of processes for the other task. For instance, presentation of the visual stimulus could serve as a warning signal, facilitating processing on the auditory task.

Finally, interactions between processes belonging to distinct tasks can be accounted for by the EPIC model (Meyer & Kieras, 1997b), according to which executive control processes prevent interference by scheduling specific task operations. The flexibility of the EPIC model makes it difficult to derive strong predictions about the exact pattern of dual-task costs, and the present results provide little evidence for or against the presence of executive systems that schedule particular computational components.

Although not directly tested in the present experiments, a likely critical feature of tasks that can be concurrently performed without interference is the lack of overlap in the input and output processes (see Van Selst et al., 1999). That is, the fact that the visual task

required manual responses and the auditory task required vocal responses might have permitted the two to be processed independently. A stronger version of this hypothesis has been proposed by Levy and Pashler (2001). Noting that spoken responses are frequently produced for auditory stimuli and that manual responses are frequently produced for visual information, they suggested that such alignments of the modalities are necessary for cost-free dual-task performance. However, other factors may be relevant. For example, in our experiments and those reported by Schumacher et al. (2001), there were spatial components in both the stimuli and responses of the visual task but none in the auditory task. It is possible that interference will arise whenever the two tasks both involve spatial components.

### Summary

The current results demonstrate that, with sufficient practice, distinct, temporally overlapping tasks can be performed nearly independently. Once this ability is developed, it remains robust over a range of test conditions. Whereas the PRP effect, the hallmark of serial response selection, has been demonstrated across a variety of tasks, cost-free dual-task performance has, to date, been demonstrated under fairly limited conditions. Further studies must determine the generality of these effects, identifying what is required to prevent conflict between overlapping tasks.

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