Simultaneous Dual-Task Performance Reveals Parallel Response Selection after Practice

Eliot Hazeltine[1], Donald Teague[2], & Richard B. Ivry[2]

[1]NASA Ames Research Center
[2]Department of Psychology, U. C. Berkeley.

IN PRESS: JEP:HPP.

Running head: Dual-task performance

Address correspondence to:
Eliot Hazeltine
NASA Ames Research Center
Mail Stop 262-4
Moffett Field, CA 94035
ehazeltine@mail.arc.nasa.gov

Date: May 29, 2001

Abstract

Considerable evidence indicates that a processing bottleneck constrains performance for temporally overlapping tasks by limiting response selection to one response at a time. However, Schumacher et al. (2001) report that dual-task costs are minimal when participants are given practice and instructed to place equal emphasis on the two tasks. We focus on whether such findings are compatible with the operation of an efficient bottleneck. In Experiment 1, participants trained until able to perform both tasks simultaneously without interference. Novel stimulus pairs produced similar reaction times to practiced pairs, demonstrating that the ability did not result from the development of compound stimulus-response associations. Manipulating the relative onset (Exps. 2 and 4) and duration (Exps. 3 and 4) of response selection processes did not lead to dual-task costs. Thus, the results indicate that the two 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? While 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 and 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 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 will briefly summarize the basic approach taken in PRP studies and review the dominant theoretical perspectives (for comprehensive reviews, see Pashler, 1994; Pashler & Johnston, 1998; Meyer & Kieras, 1997b). 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 reaction times at long SOAs compared to short SOAs. In contrast, factors presumed to lengthen response-selection processes on the second task produce increases in task 2 reaction times 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 reaction time on the second task is implicit in the task instructions (see Meyer et al., 1995; Meyer & Kieras, 1997b). 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 response might also reflect strategic decisions made by participants to focus on the first task until it is completed. According to this account, the patterns of reaction time have little to do with structural limitations of human cognition (Meyer & Kieras, 1997a). Although the PRP effect is robust when incentives are provided to decrease reaction times on both tasks (e.g. Ivry, Franz, Johnston, & Kingstone, 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).

Evidence that the bottleneck is strategic rather than a structural feature of human cognition has been obtained with PRP designs (Meyer, Kieras, Lauber, Schumacher, Glass, Zurbriggen, Gmeindl, & Apfelblat, 1995; Schumacher, Lauber, Glass, Zurbriggen, Gmeindl, Kieras, & Meyer, 1999). The basic result in these studies is that factors presumably affecting response selection on task 1 lead to smaller reaction time 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 subjects. 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, Johnston, & Ruthruff, 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, Johnston, and Ruthruff (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 & Jolicoeur, 1997), these researchers used an auditory-vocal task and visual-manual task. These pairings ensured that both 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, reaction times for the second task at the shortest SOA were still 40 ms longer than 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 process should largely determine the magnitude of the PRP effect.[1] 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 should expect practice to predominantly facilitate response selection since it is this stage that constitutes the novel aspect of the tasks. In sum, these training studies demonstrate that while 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), who used a similar paradigm, although the participants were less practiced.

As an alternative to the CB model, Meyer and Kieras (1997a) proposed EPIC (Executive Process/Interactive Control) 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 in order to ensure that there are no conflicting demands for peripheral resources. A PRP-like pattern of reaction time emerges from the increased need of the delays at shorter SOAs.

The results of Schumacher et al. (2001) are consistent with the EPIC model in 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 0. After extensive practice, such processes for the visual-manual and auditory-vocal tasks may be fairly short (Van Selst, Johnston, & Ruthruff, 1999; Ruthruff, Johnston, &Van Selst, in press) and may not overlap due to differences in the durations of pre-bottleneck components for the two tasks. This account could certainly lead to largely reduced interference, even though a CB would still be in effect. We address 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 stimulus, 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 stimulus-response 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 two-fold: 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 using the PRP paradigm, decrements in the PRP effect have closely tracked the reduction in the reaction times for one of the tasks. In the present experiment, we examined the relationship between the reductions in the dual-task costs and the single-task reaction times 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 the participants gave a vocal response based on the pitch of the stimulus. For the visual-manual task, a visual stimulus would appear at one of three spatial positions and the 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.

Methods.

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 the computer monitor. Each circle subtended approximately 1 degree of visual angle, and the possible locations were separated by approximately 0.8 degrees of visual angle. Three white lines that served as placeholders for the possible locations were continuously present on the screen, approximate 0.5 degrees below the location of the circles. The circle remained visible until the participant responded or until a 2000 ms inter-response 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 internal speaker in the computer. The tones lasted 150 ms and were 220 Hz, 880 Hz, or 3520 Hz. Participants responded according to the frequency by saying “one”, “two”, or “three”, for the low, middle, and high pitch sounds, respectively. The participants’ vocalization activated a voice key, also connected to the computer, so that an accurate measurement of the vocal reaction time could be acquired. The experimenter typed the actual response on the computer keyboard so that the 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 of the visual task and 15 of 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), trials occurring in the single-task blocks were termed single-homogeneous (S-Hom) trials, and single-task trials in the dual-task blocks were termed single-heterogeneous (S-Het) trials. For 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 represent 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 reaction times. The target times were equal to the mean reaction times 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 and dual-task blocks based on these criteria. To ensure that the participants continually sought to respond as quickly as possible, the target times were reduced whenever the mean reaction time for a particular condition was lower than the corresponding target time.[2]

Participants performed multiple sessions of the two tasks during training. When possible, sessions were scheduled on consecutive days. All participants completed the training within two 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 block of each type and 6 dual-task blocks. Each subsequent session proceeded as follows: Participants would begin 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 pseudo-randomized across participants and sessions. Transfer sessions were identical to training sessions, except that the dual-task blocks contained an additional 9 dual-task trials, consisting of the new combinations. All other aspects were the same and the 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 task conditions. Once a participant's reaction times 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 transferred to the transfer sessions in which the new dual-task pairings were introduced. For all of the analyses, reaction times that were 3 standard deviations from the mean were removed from the data. Trimming the data using this criterion removed less than 1% of the reaction times 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 two 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 are unique in that subjects are able to anticipate the 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 reaction times for each trial type for each participant were computed after eliminating trials with incorrect responses on either task. The resulting mean reaction times (Figure 1) were submitted to a one-way ANOVA with trial-type (S-Hom, S-Het, D-Old, and D-New) as the factor and participant as the repeated measure. There was no effect of trial-type for either the visual [$F(3, 24) < 1$; MSE = 97.75] or the auditory task [$F(3, 24) = 2.23$; $p > 0.1$; MSE = 110.71].

Please insert Figure 1 about here.

Identical analyses were performed on the accuracy data (Figure 1). There was a significant effect of trial type for the visual task [$F(3, 24) = 3.82$; $p < 0.05$; MSE = .001] but not for the auditory task [$F(3, 24) < 1$; MSE = .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.

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 8 training sessions, the mean cost was essentially 0 ms for the visual task and a non-significant 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, Ruthruff, and Johnston (1999) observed a PRP effect of nearly 50 ms after even more extensive training than that employed 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-tasks 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, then it would embody an important feature of S-R learning (cf. Pashler & Baylis, 1991). This possibility is 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 the 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 above.

These data were submitted to a two-way ANOVA in which one variable represented the time period and the other variable represented the trial-type: single-homogeneous, single-heterogeneous, and dual-old. Because the dual-new trials occurred only during the final time period, these data were not included in the analysis. For both the visual and auditory tasks, there was a significant period x trial-type interaction [visual: $F(4, 32) = 5.57$; $p < .005$; MSE = 276.55; auditory: $F(4, 32) = 4.42$; $p < .01$; MSE = 187.90), indicating that the decrease in reactions times 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.

Please insert Figure 2 about here.

The greater reductions in reaction times for the dual-task trials were expected, since 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 takes practice. For the visual task, the reductions in reaction times 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 stimulus-response mapping for the auditory task was less compatible than the mapping for the visual task.

Correlations. An alternative analytic approach is to look at the trial-by-trial correlations in the reaction times for the visual and auditory tasks. In dual-task experiments with short (or 0 ms) SOAs, correlations in reaction times 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, 1994). Thus, speed-ups or delays in completing CB processes on the first task lead to corresponding speed-ups 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 following extended practice, one based on the idea of non-overlapping response selection and the other 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 central bottleneck in a consistent order, then reaction times 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 the reaction times on dual-task trials should be near zero.

To examine this issue, the correlation between reaction times for the visual and auditory tasks on the dual-task trials was calculated for each participant. For the test sessions, the correlations were weak but significantly greater than 0 for both the trained pairs and untrained pairs [dual-old mean: 0.21; sd= 0.17; $\underline{t}(8) = 3.58$; $\underline{p} < 0.005$ (one-tailed); dual-new mean: 0.18; sd= 0.17; $\underline{t}(8) = 3.09$; $\underline{p} < 0.01$]. The calculated slopes for the regression were also unimpressive: the mean slope for the dual-old trials was 0.28 (sd .26) and the mean slope for the dual-new trials was 0.21 (sd: .21). These correlations are smaller and the slopes shallower than those reported in PRP experiments (e.g. Pashler & Johnston, 1989; Van Selst et al., 1999; see also, Pashler, 1994). Nonetheless, these findings could be accommodated by the CB model if post-bottleneck processes contributed most of the variability to the reaction times.

In sum, 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 compared to single-task trials, and the reaction times 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 stimulus-response 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 test 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 reaction times 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 prior to 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 employing a sequential strategy when performing the two tasks. Participants could be 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 prior to 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.

Please insert Figure 3 about here.

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 response 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 may have been inferred from exposure to the practiced combinations (cf. Pashler & Baylis, 1991). Again, we would expect the correlation between the reaction times for the two tasks to be somewhat stronger than what was observed, but relatively high variance in post-selection 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 reaction times on the slower, auditory task. As depicted in Figure 3, increasing the processing time required prior to 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 reaction time for both tasks if the two tasks sequentially access the response selection bottleneck (Figure 3B).[3]

There are two possibilities to consider if response selection occurs in a compound manner for the two tasks. First, the reaction times for both tasks might become slower because the processing time prior to selection is increased (Figure 3C). Second, there may be little observed increase in the reaction time 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 (panel D). In either case, the compound selection model does not predict that prolonging visual stimulus classification will produce larger effects on visual RT compared to 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 borrow 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.

Our focus in Experiment 2 was to test the hypothesis that the lack of a dual-task cost in Experiment 1 occurred because the participants were able to complete the CB operation for the visual task prior to when 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 therefore be treated with caution since the participants may benefit 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 introduces 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 seven of the nine 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 subject's data revealed that he had achieved the dual-task performance criteria by the last 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 the 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 candelas/m^2, whereas the target circle was 26.4 cd/m^2. 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 both in terms of brightness and location, whereas the easy task only required a discrimination of location.

Procedure.

For six 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 six months separated the two experiments. This participant was first re-tested on three transfer sessions of Experiment 1. Once performance on the dual-task trials matched that achieved on single-task conditions (using 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 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/single task block; 114 trials/dual-task block with 54 of these dual-task trials). Participants completed 4 single-task blocks (2 auditory and 2 visual) and 9 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 reaction times and error rates for each of the 3 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 [$F(2, 12) = 10.42$; $p < .005$; MSE = 90.89] and Discriminability [$F(1, 6) = 158.44$; $p < .0001$; MSE = 178.21]. The effect of Discriminability indicated that participants were faster on easy trials (286 ms) compared to the hard trials (338 ms). Thus, our manipulation of discriminability was effective.

Please insert Figure 4 about here.

The effect of Trial-type was due to reaction times being slowest when the visual task was performed alone (S-Hom blocks). This finding mirrors the decrease in accuracy for this 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 x Discriminability interaction [$F(2, 12) = 6.28$; $p < .05$; MSE = 11.69]. CB models cannot readily account for the fact that the cost for hard discriminations was greater on dual-task trials than the cost associated with easy discriminations. This is because 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 reaction times for the hard S-Het and dual-task trials were essentially identical, and the interaction was driven by slower reaction times for the easy S-Hom trials. Therefore, the small difference (8 ms) in the 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. For the first ANOVA we included the single task auditory conditions (S-Hom, 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, since we limited this analysis to the easy visual trials, this analysis essentially looks at a replication of conditions from Experiment 1. The analysis revealed a highly significant effect of Trial-type [$F(2, 12) = 25.77$; $p < .0001$; 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 mirrors a smaller, non-significant trend observed in Experiment 1.

Importantly, little single-task advantage was observed when comparing the S-Het and Dual trials. This suggests that the single-task benefit for the 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 reaction time 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 of manipulating the stimulus for the visual task on the auditory task. The effect of Discriminability was significant [$F(1, 6) = 30.38$; $p < .005$; MSE = 36.64]. Thus, in accord with the CB model, delaying response selection for the visual task did lengthen reaction times on the auditory tasks. However, the magnitude of the effect was significantly smaller for the auditory task than it was for the visual task [$t(6) = 6.24$; $p < .001$ (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 fashioned 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, reaction times for this task on the dual-task trials were divided into quintiles for each subject 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 be largest for trials with the shortest auditory reaction times. This is because trials with short auditory reaction times are those in which response selection for the visual task is most likely to extend into the period in which pre-selection processes for the auditory task are complete. In fact, the pattern of costs on the auditory task for the hard visual trials is exactly the opposite: Discriminability has the smallest effect for auditory reaction times in the fastest quintile and had the largest effect for auditory reaction times in the slowest quintile, resulting in a significant linear trend [$F(1,33) = 19.54$; $p < .0001$; MSE = 110.06]. Moreover, when the data are divided into quintiles according to speed on the visual task, the effect of Discriminability on the auditory task is essentially constant across quintile, 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. Among these, only the effect of discriminability in the visual task was significant [$F(1, 6) = 62.01$; $p < .0005$; MSE = .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 reaction times on the dual-task trials, with a mean 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 [$t(6) = 1.81$; $p > .1$].

Inter-response intervals. When the visual discrimination was hard, the reaction times 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 post-bottleneck processes. Such a reaction time 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 inter-response interval was tabulated for each trial by subtracting the visual RT from the auditory RT. The distribution of the inter-response intervals is shown in Figure 5. Although the distribution is mildly negatively skewed, it is clearly unimodal, and there is no evidence that any interval between the two responses is under-represented. Thus, the difference scores provide further evidence against the idea that a CB is successively engaged by the two tasks.

Please insert Figure 5 about here.

In sum, Experiment 2 provides further evidence against the hypothesis that a central bottleneck constrains performance during 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 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 reaction times. 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 compared to the S-Hom trials. Participants are likely to have a different set when responding to single task trials when tested alone compared to when these trials are embedded in a multi-task context (see Allport, 1994). This change in set likely reflects the allocation of resources.

Experiment 3

While 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 stimulus-response mapping is highly compatible (Greenwald & Shulman, 1973; Pashler, 1994; Pashler, Carrier, & Hoffman, 1993). In our experiments there is no obvious compatibility between the tones and the vocal responses "one", "two", and "three". In contrast, a high degree of compatibility exists 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 a special condition 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 6 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 compare performance on two different S-R mappings for the visual task. Consequently, we can assess how lengthening response selection processes for one task affects performance of the other task. In particular, the inclusion of two mapping conditions allows us to determine the degree to which increases in reaction times 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 1-2). Differences in the visual task reaction times 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 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 if any dual-task cost was also seen on the auditory task.

Method.

Participants. The seven 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 those used for the previous experiments. Participants were retrained on the basic task using the same procedures as in Experiment 1 until they met the dual-task performance criteria.[4] 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 leftmost circle appeared, participants were to press the leftmost key (i.e., the S-R mapping for this stimulus remained consistent). When the center circle appeared, they were to press the rightmost key, and when the rightmost 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.

Each participant completed two test sessions, each of which consisted of 2 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 on one session and with the incompatible condition in the other session. Each half consisted of 7 blocks whose order was fixed: single-task (auditory), single-task (visual), dual-task, dual-task, single-task (visual task), dual-task, and dual-task. After completing this sequence of blocks, the new S-R mapping for the visual task was explained, and then the sequence was repeated. Dual-task blocks consisted of 36 dual-task trials and 36 single-task trials. For the dual-task trials, 4 trials for each of the 9 possible location-tone combinations were presented. Of the 36 single-task trials, 18 trials 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 trials per block, composed of 20 trials on each of the 3 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 reaction times and accuracy of the 4 trial-types for the two visual conditions are shown in the top panel of Figure 6. As is evident, there was a highly significant effect of Mapping [$F(1, 6) = 87.68$; $p < .0001$; MSE = 498.55], but no effect of Trial-type [$F(2, 12) = 1.34$; $p > .2$; MSE = 103.77] and no Mapping x Trial-type interaction [$F < 1$]. This pattern indicates that, although the hard mapping condition added 65 ms to reaction times 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 is especially impressive, given the potential interference between the two mappings and the participants' limited exposure to the new response assignments.

Please insert Figure 6 about here.

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 had only three stimulus-response 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 participated in Experiments 1 and 2 and had at least 10 sessions with the auditory task and compatible visual S-R mapping condition prior to 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 two tasks. Schumacher et al. (2001) tested naïve 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 of the participants rather than a restricted subset as in Schumacher et al.

The reaction time 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 analysis of the data from the auditory task consisted of 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 used only the data from the compatible mapping condition and included all 3 trial-types. As in Experiment 2, reaction times for the S-Hom trials were faster by 15 ms than 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 the mean reaction times on the S-Het trials were within 2 ms of the mean reaction times 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 used a Trial-type factor that consisted of 2 levels: S-Het and Dual, along with the Mapping factor that consisted of 2 levels: compatible and incompatible. Both factors produced significant effects [Trial-type: $F(1, 6) = 6.14$; $p < .05$; MSE = 15.74; Mapping: $F(1, 6) = 22.97$; $p < .005$; 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 the 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 [$F(1, 6) = 33.81$; $p < .005$; MSE = 5.48]. The interaction between Mapping and Trial-type was due to the fact that the increase in auditory reaction times during the blocks with the incompatible visual mapping was greater on Dual trials compared to the 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 vs. 18 ms for S-Het and Dual, respectively), compared to 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 the 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 cost 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 was performed first would have shorter reaction times, and these would show no transfer of the mapping effect from the visual task.

To examine this possibility, reaction times for the two trial-types within each level of mapping were divided into quintiles, and quintiles for the incompatible mapping were subtracted from corresponding quintiles for the compatible mapping. The faster quintiles did show smaller effects of mapping, and this trend was significant for the Dual trials [fastest quintile: 16 ms cost; slowest: 26 ms cost; linear trend: $F(1, 33) = 4.58$; $p < .05$; MSE = 83.88]. This pattern was not observed in the S-Het trials (fastest quintile: 10 ms; slowest: 6 ms). Importantly, the magnitude of the effect is 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 et al. (2001) have argued that with extensive practice, computations that initially occur during the bottleneck stage can be shifted to occur prior to 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 pre-bottleneck 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 only for reduced effects on the manipulated task itself and not for reduced effects of the other task.

Identical ANOVAs were performed on the accuracy data. For the visual task, only the effect of Mapping was significant [$F(1,6) = 24.94$; $p < .005$; MSE = .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 = .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 [$t(6) = 1.67$; $p > .1$].

Correlations. Increasing the difficulty of the S-R mapping had little effect on the correlations between the reaction times for the two tasks as they remained quite low, with a mean of 0.22 (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 down response times 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 when considering that the participants had little practice with the incompatible mapping prior to the first test session. Whatever participants had learned to enable them to perform the two selection processes simultaneously in Experiments 1-2, 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 participant performed the easy visual mapping and only a 10 ms difference when they performed the hard mapping. Given that the mapping is assumed to affect bottleneck processes[5], 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 reaction times.

In sum, 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 pre-bottleneck 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.

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 finding robust interference between two temporally overlapping tasks? One obvious factor is practice: cost-free dual-task performance was only evident 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 employing the analytic power of the PRP method, the stimuli for the two tasks are generally 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 introduce 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 produces 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 discernable 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 have assumed that response selection for the visual task must be occurring first because, under compatible conditions, this task was about 50 ms faster than the auditory task. Though unlikely, it is possible that selection for the auditory task occurred first, but that the responses were slower because of differences in post-selection 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 happening 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 the 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 had 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 has some important advantages in the present context. First, it is commonly used in PRP experiments, allowing ready comparisons between this experiment and others, where 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 to delays that result from the stimulus onsets. If the small dual-task costs observed in the preceding experiments occur because of general resource limitations, then the SOA manipulation should have no effect on the 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 what was observed with the manipulations of discriminablility 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 expect these would induce the 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 here is to test the hypothesis that these highly trained individuals have 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 seven individuals who had participated in Experiments 1-3 were tested in Experiment 4.

Stimuli. The stimuli were identical to those used in Experiments 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. For the remaining 18 dual-task trials, the presentation of the stimuli was simultaneous as in the previous experiments. After completing the test sessions, participants were interviewed to determine if they 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 presented 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 if the results of Experiment 3 replicate when the SOA is no longer constant. For this analysis, there was a Mapping factor (compatible vs. incompatible) and a Trial-type factor (S-Hom, S-Het, and Dual). The compatible mapping trials were performed 52 ms more quickly than the incompatible mapping trials [$F(1, 6) = 152.42$; $p < .0001$; MSE = 190.05], but the neither the effect of Trial-type nor the Mapping x Trial-Type interaction approached significance [F's <1]. In short, there appears to have been little cost for performing the two tasks simultaneously for the 0 SOA trials, replicating the results of Experiment 3.

Please insert Figure 7 about here.

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, visual stimulus first). As in the first ANOVA, only the effect of Mapping was significant [$F(1, 6) = 136$; $p < .0001$; MSE =

210.10]. The effect of SOA did not approach significance [$F < 1$], suggesting that relative onsets of the two stimuli had little effect on the performance of the visual task.

To evaluate dual-task performance on the auditory task, the data from the compatible mapping condition, excluding those trials on which the stimuli were not presented simultaneously, were submitted to a one-way ANOVA with a three level (S-Hom, S-Het, Dual) Trial-type factor. The S-Hom trials were performed more quickly than the other Trial-types [$F(2, 12) = 12.33$; $p < .005$; 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 reaction times 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 used the compatible mapping compared to when the visual task used the incompatible mapping [$F(1, 6) = 38.60$; $p < .001$; MSE = 47.33], closely replicating the findings in Experiment 3. The effect of SOA [$F(2, 12) = 20.89$; $p < .0005$; MSE = 30.54] is shown in the bottom panel of Figure 7. On average, auditory reaction times were 14 ms faster when the visual stimulus appeared first compared to when the auditory stimulus appeared first, with the reaction times 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 response times. The Mapping x SOA interaction did not achieve significance [$F(2,12) = 2.79$; $p > .1$; 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 that the 50 ms handicap would have had a large effect on these proportions and consequently produced 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; $F(1, 6) = 21.53$; $p < .005$; 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]. For the SOA ANOVA, the dual-task trials in which the auditory stimulus was presented first were performed less accurately than the other dual-task trials [.88 vs. .92 and .93, for the auditory first, simultaneous, and visual first, respectively, averaged across the two mappings; $F(2, 12) = 9.08$; $p < .005$; MSE = 0.001]. This latter effect indicates that, contrary to the findings from the reaction time 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 reaction times—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 in the reaction times for the visual task (the means are within 4 ms for the 3 SOAs).

Correlations. The correlations between the reaction times for the visual and auditory tasks were smaller than those observed in the previous experiments, with a mean of 0.15. A two-way ANOVA on the correlations between the reaction times 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 (mean= 0.03; sd=0.16). In contrast, the correlations for the simultaneous (mean=.20; sd=.18) and visual stimulus first (mean=.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, then 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 reaction times 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 reaction times for the two tasks, the CB model imposes limits on the intervals that can exist between the two responses. Because selection 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 post-selection processes. The combination of different SOAs and S-R mappings in Experiment 4 offers 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 inter-response intervals are plotted as a function of the mapping and SOA in Figure 8. As can be seen, the set of distributions spanned approximately 150 ms and there was little evidence of any 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.

Please insert Figure 8 about here.

In sum, 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 stimulus-response 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.

While 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 small effects on dual-task performance. The two tasks appear to be performed nearly independently. For the visual task, the mean reaction times for all conditions within each of the mapping levels were within 12 ms of each other. For the auditory task, the reaction times were within 34 ms of each other. Thus, while 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 that postulate 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 presented in this paper provide a detailed look at dual-task performance in practiced individuals. Most of the prior work on this problem has focused on relatively crude measures of performance (e.g., Spelke, Hirst, & Neisser, 1976) or used 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, Johnston, & Ruthruff, 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 the 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 compared 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 central bottleneck associated with response selection that persists throughout practice. The 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 the reaction times 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 et al., in press). If so, then the 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 employed in Experiments 2-4. Delaying (Experiments 2 & 4) or lengthening (Experiments 3 & 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 reaction times for the auditory task were consistently slower than the visual-manual reaction times 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 the visual-manual reaction times and only a small impact on the auditory-vocal reaction times, 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 be 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 reaction time interval. Therefore, it is reasonable to ask how long a bottleneck stage could last while remaining essentially undetected by 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 non-bottleneck 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 the 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 reaction times, limiting the range of stage durations for the two tasks. Moreover, the reaction times 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 pre-bottleneck stage (Stage A), a bottleneck stage (Stage B), and a post-bottleneck stage (Stage C). The sum of the durations of these stages was, by definition, the reaction time 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 want to determine the temporal extent of a unitary bottleneck stage that would be undetected in our experiments, we have 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 different duration for the two tasks. For example, response selection for the visual-manual task could be shorter than 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 non-bottleneck 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 the stages were constant with zero variance. While this assumption is clearly unrealistic, it is unlikely to produce inflated measures of interference. Although shorter than average stage durations can potentially alleviate interference, by the same token, 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, a maximum amount of allowable interference had to be chosen. 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 last more than 10 ms.

With these assumptions, many degrees of freedom remain. For a given set of durations of the four non-bottleneck 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 non-bottleneck stages, the durations of the two bottlenecks are fungible, so that time can be transferred from the bottleneck stage of one task to the other without changing the amount of interference. However, because the mean reaction times for the two tasks differed, 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 for this simulation are shown in Figure 9. The x- 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).

Please insert Figure 9 about here.

As can be seen, bottleneck stages lasting between 20 to 40 ms are possible across a range of Stage A combinations. Less likely 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 reaction time period. The simulation also makes explicit the idea that the benefits of practice are likely 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 visuals tasks are 100 ms and 130 ms, respectively, then overlap for the two bottleneck stages is observed only when 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 are the opposite: The RT on the auditory task is slower when the tone is presented prior to the visual stimulus. Indeed, many of the combinations producing acceptable dual-task costs, 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 only found for combinations in which Stage A is much longer for the auditory task compared to the visual task. For example, if Stage A was 100 ms for the visual task and 170 ms for the auditory task, then two 30 ms bottleneck stages would only overlap for the tone-first SOA and here the auditory response would be delayed 10 ms. Combinations involving very different Stage A durations comprise 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 B for the task first requiring the bottleneck would necessarily be passed on to the other task. Not only would such carry-over result in larger dual-task costs, but it would also lead to correlations between the reaction times for the two tasks. Although significant correlations were observed, these were much weaker than those reported using 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 reaction times increased by 52 and 13 ms for the visual and auditory tasks, respectively. The increases in the visual task reaction times would traditionally be considered to reflect increases in the bottleneck stage, because only the S-R mapping is changed. However, if the bottleneck stage for the visual task is 80 ms long (30 ms + 50 ms), then 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, each processing stage 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, we note that the difficulty of the auditory task was not manipulated in any of the experiments. This raises the possibility that, following extensive practice, performance on the auditory task can bypass a central bottleneck associated with response selection. Such a hypothesis would be consistent with the failures 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 is arbitrary so it seems unlikely that response selection here would bypass a general response selection module, should one exist. Second, the reaction times on the auditory task continued to decrease across the four experiments: Considering the performance on the S-Het trials of the seven participants who completed all of the experiments, the mean reaction time 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 is also 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 the dual-task interference diminishes as the one or both of the tasks become automatized.[6] 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 does not allow us to determine if one or both tasks have become 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 produce extensive interference on our auditory-vocal task even with our practiced participants.

Implications for the study of multi-task performance.

Given the large body of work showing robust interference effects that are elegantly characterized by the response selection bottleneck model, our results were quite unexpected. Not only do they appear 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: Reaction times for the auditory task were constant across SOA and reaction times for the visual task were negatively correlated with SOA. Because these same subjects 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 reaction times were the product of a strategy employed to prevent the response for task 2 from preceding the response for task 1.

The SOA manipulation we used in Experiment 4 provides 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 observed 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 based on its perceived length. With the implicit manipulation of SOA, the effects of SOA can be observed without strategic influence.

While 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 would be available for processing the auditory task, leading to slower reaction times. The carry-over 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, the presentation of the visual stimulus could serve as a warning signal, facilitating the processing on the auditory task.

Finally, interactions between processes belonging to distinct tasks can be accounted for by the EPIC model (Meyer & Kieras, 1997b), in 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.

Though not directly tested in these 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 (under review). Noting that spoken responses are frequently produced for auditory stimuli and that manual responses are frequently produced for visual information, they suggest 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 are spatial components in both the stimuli and responses of the visual task, but none in the auditory task. It is possible that interference would 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. While 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.

References

Allport, A., Styles, E.A., & Hsieh, S. (1994). Shifting intentional set: exploring the dynamic control of tasks. In C. Umilta and M. Moscovitch (Eds.), Attention and Performance XV. Cambridge, MA: MIT Press (pp. 421-452).

Anderson, J.R. (1983). The architecture of cognition. Cambridge, MA: Harvard University Press.

De Jong, R. (1993). Multiple bottlenecks in overlapping task performance. Journal of Experimental Psychology: Human Perception and Performance, 19, 965-980.

Greenwald, A.G., & Shulman, H. (1973). On doing two things at once II: Elimination of the psychological refractory period. Journal of Experimental Psychology, 101, 70-76.

Hommel, B. (1998). Automatic stimulus-response translation in dual-task performance. Journal of Experimental Psychology: Human Perception and Performance, 24, 1368-1384.

Ivry, R. B., Franz, E. A., Kingstone, A., & Johnston, J. C. (1998). The PRP effect following callosotomy: Uncoupling of lateralized response codes. Journal of Experimental Psychology: Human Perception and Performance, 24, 463-480.

Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. Quarterly Journal of Experimental Psychology, 20, 167-178.

Levy, J. & Pashler, H. (under review). Is dual-task slowing instruction dependent?

Logan, G.D. (1988). Toward an instance theory of automatization. Psychological Review, 95, 492-527.

MacLeod, P. A. & Posner, M. I. (1984). Priviledged loops from percept to act. In H. Bouma & D. Bowhuis (Eds.), Attention and Performance X, Hillsdale, NJ: Erlbaum.

McCann, R. S. & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. Journal of Experimental Psychology: Human Perception and Performance, 18, 471-484.

Meyer, D. E. & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: I. Basic mechanisms. Psychological Review, 104: 3-65.

Meyer, D. E. & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. Psychological Review, 104: 749-791.

Meyer, D. E., Kieras, D. E., Lauber, E., Schumacher, E. H., Glass, J., Zurbriggen, E., Gmeindl, L., Apfelblat, D. (1995). Adaptive executive control: Flexible multiple-task performance without pervasive immutable response-selection bottlenecks. Acta Psychologia, 90, 163-190.

Pashler, H. (1989). Dissociations and dependencies between speed and accuracy: Evidence for a two-component theory of divided attention in simple tasks. Cognitive Psychology, 21, 469-514.

Pashler, H. (1994). Graded capacity-sharing in dual-task interference? Journal of Experimental Psychology: Human Perception & Performance, 20, 330-342.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. Psychological Bulletin, 116, 220-244.

Pashler, H. (1998). The psychology of attention. The MIT Press, Cambridge, MA.

Pashler, H. & Baylis, G. (1991). Procedural learning: 1. Locus of practice effects in speeded choice tasks. Journal of Experimental Psychology: Learning, Memory and Cognition, 17, 20-32.

Pashler, H., Carrier, M., & Hoffman, J. (1993). Saccadic eye movements and dual-task interference. Quarterly Journals of Experimental Psychology, 46A, 51-82.

Pashler, H. & Johnston, J.C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 41, 19-45.

Pashler, H., & Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. Pashler (Ed.) Attention (pp. 155-189). Hove, UK: Psychology Press.

Ruthruff, E., Johnston, J. C., & Van Selst, M. (2001). Why practice reduces dual-task interference. Journal of Experimental Psychology: Human Perception and Performance, 27, 3-21.

Ruthruff, E., Miller, J. O., & Lachmann, T. (1995). Does mental rotation require central mechanisms? Journal of Experimental Psychology: Human Perception and Performance, 21, 552-570.

Ruthruff, E., Pashler, H. E., Klaassen, A. (2001). Processing bottlenecks in dual-task performance: Structural limitation or strategic postponement? Psychological Bulletin and Review, 8, 73-80.

Schumacher, E. H., Lauber, E. J., Glass, J. M., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (1998). Concurrent response-selection processes in dual-task performance: Evidence for adaptive executive control of task scheduling. Journal of Experimental Psychology: Human Perception and Performance, 25, 791-814.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central attentional bottleneck. Psychological Science, 12, 101-108.

Simon, H. A. (1994). The bottleneck of attention: Connecting thought with motivation. In: William D. Spaulding, (Ed.) Integrative views of motivation, cognition, and emotion. (pp 1-21). University of Nebraska Press: Lincoln.

Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. Cognition, 4, 215-230.

Telford, C. W. (1931). Refractory phase of voluntary and associative responses. Journal of Experimental Psychology, 14, 1-35.

Van Selst, M., & Jolicoeur, P. (1997). Decision and response. Cognitive Psychology, 33, 266-307.

Van Selst, M., Ruthruff, E. & Johnston, J. C. (1999). Can practice effects eliminate the psychological refractory period effect? Journal of Experimental Psychology: Human Perception and Performance, 25, 1268-1283.

Acknowledgments.

The authors wish to thank James Johnston, Eric Ruthruff, Roger Remington, Hal Pashler, David Meyer, and an anonymous reviewer for many useful suggestions and comments on earlier drafts. Support for this work was provided by the National Institute of Health (NS30256, NS1778) and the National Science Foundation (ECS-9873474).

Figure Captions.

1. Mean reaction times for the four trial types are shown for the visual (labeled VM, left) and auditory (labeled AV, right) tasks. The proportions of correct responses for the 4 trial types are printed above the appropriate columns.
2. Mean reaction times for the two tasks shown as function of training.
3. Stages of processing depicted for the two tasks. In panel A, response selection for the visual task occurs before selection for the auditory task, minimizing interference. In panel B, selection is delayed for the visual task by lengthening stimulus classification processes, pushing it into conflict with selection for the auditory task. In panel C, delays induced by lengthening classification for the visual task are conferred to the auditory task when a compound selection process is used. In panel D, the lengthening of stimulus identification for the visual task is absorbed in to the slack created by the compound selection process, which must not begin until the auditory stimulus identification is completed.
4. Mean reaction times and proportion correct for the visual task (top panel) and auditory task (bottom panel) in Experiment 2.
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 from the reaction time for the auditory task.
6. Mean reaction times and proportion correct for the visual task (top panel) and auditory task (bottom panel) in Experiment 3.
7. Mean reaction times for the visual task (top panel) and auditory task (bottom panel) in Experiment 4. For the dual-task trials, the data are divided in terms of the SOA. Reactions 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 V.
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 SOA.
9. Maximum durations of bottleneck stages that might go undetected in the easy mapping condition of Experiment 4. The x-axis represents a range of values for the duration of the pre-bottleneck 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 panel depicts the possible durations for the auditory-vocal task bottleneck stage (Stage B) assuming that this stage lasts 30 ms for the visual-manual task. Bottom panel depicts the possible durations for Stage B for the visual-manual task bottleneck stage assuming that this bottleneck stage lasts 30 ms for the auditory-vocal task. Maximum bottleneck durations less than 20 ms are indicated by white, those between 20-40 ms are indicated by the stippled pattern, and those between 40-60 ms are indicated by black.

Footnotes.

1. The length of the stimulus classifications processes for both task 1 and task 2 also contribute to the magnitude of the PRP (see Ruthruff, Johnston, & Van Selst, in press), but if one assumes that these processes stay fairly constant across practice then response selection for task 1 should primarily determine the size of the effect.

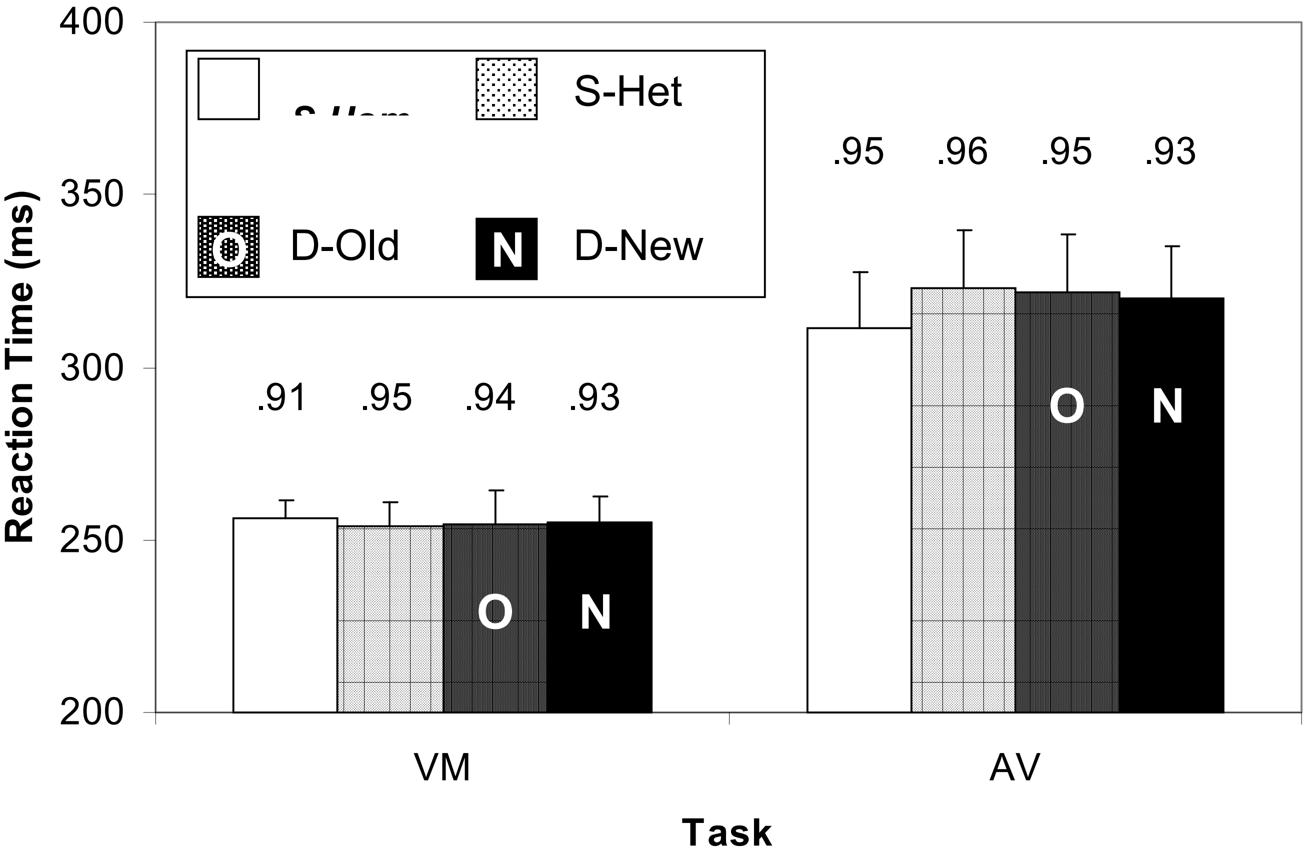
2. When participants reaction times for given block were less than 100 ms greater than the corresponding target time, they received an additional 10 cents for that block. When the reaction time was less than 50 ms, they received an additional 25 cents, and when the reaction time was faster than the target time, they received and 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 based on accuracy so that 0.5 cent was given for each correct response and 5 cents were deducted for each incorrect response.

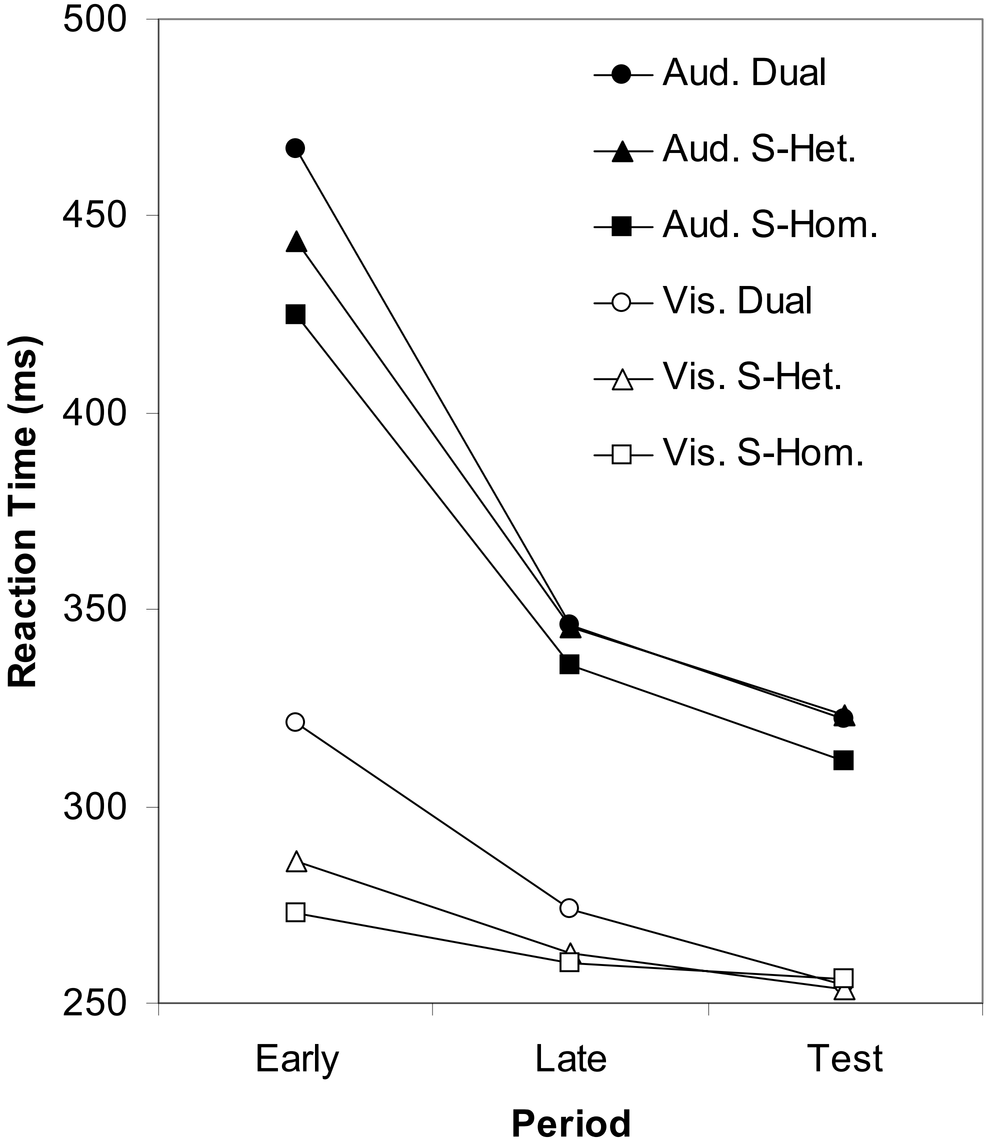
3. It is possible that, by making the visual task harder, the order in which the two tasks access the selection process might be reversed. Thus, we might find little dual-task cost because the selection for the auditory task is always completed prior to the visual task. Though unlikely, we examine this hypothesis in Experiment 4.

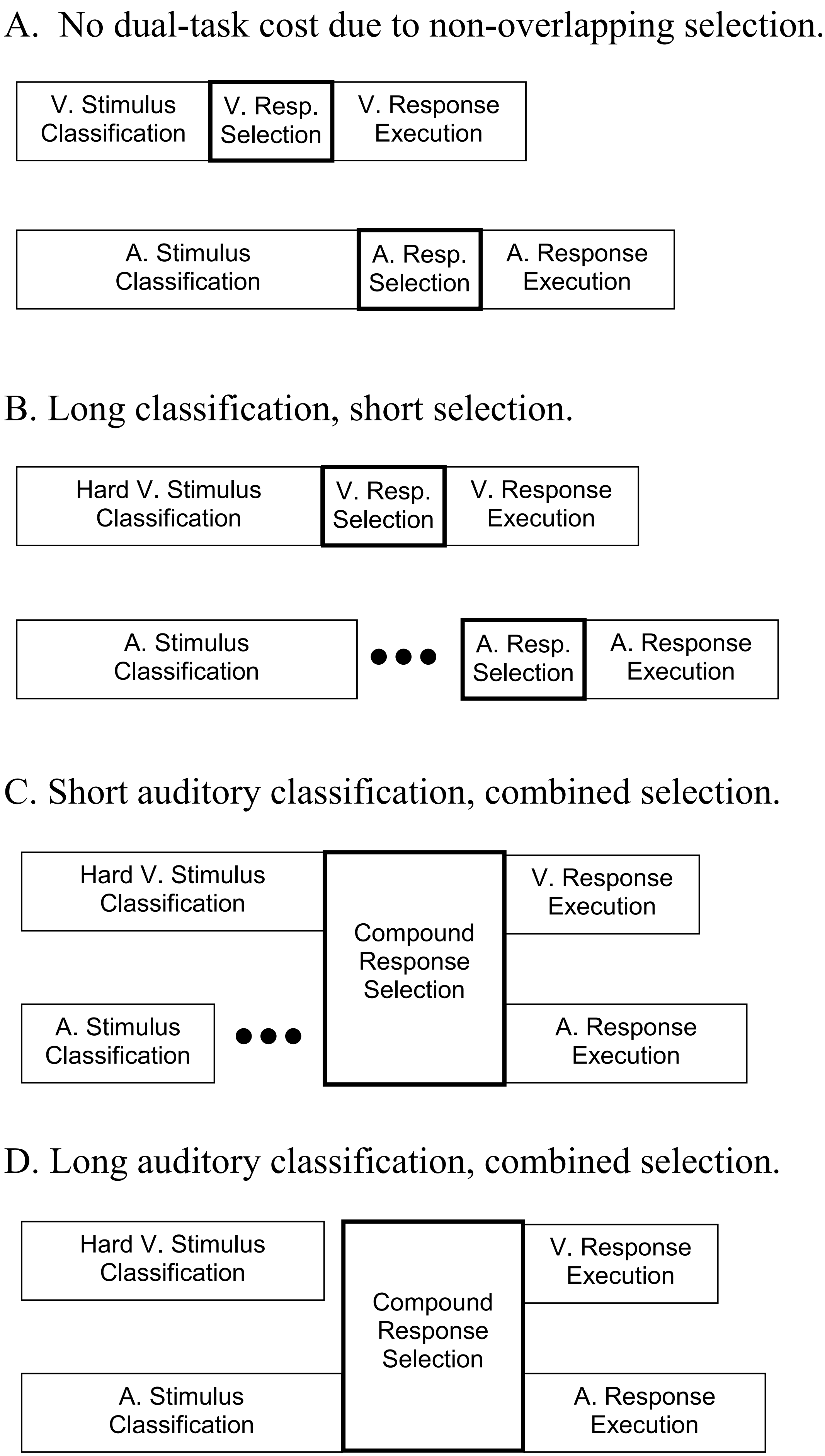
4. Three of the 7 participants performed an earlier version of Experiment 3 between Experiment 2 and the version of Experiment 3 reported here. Thus, these participant had performed 2 sessions with the incompatible mapping approximately 5 weeks before beginning Experiment 3. In the initial version of Experiment 3, we did not include the blocks with the compatible mapping. The results were highly consistent with those reported in 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.

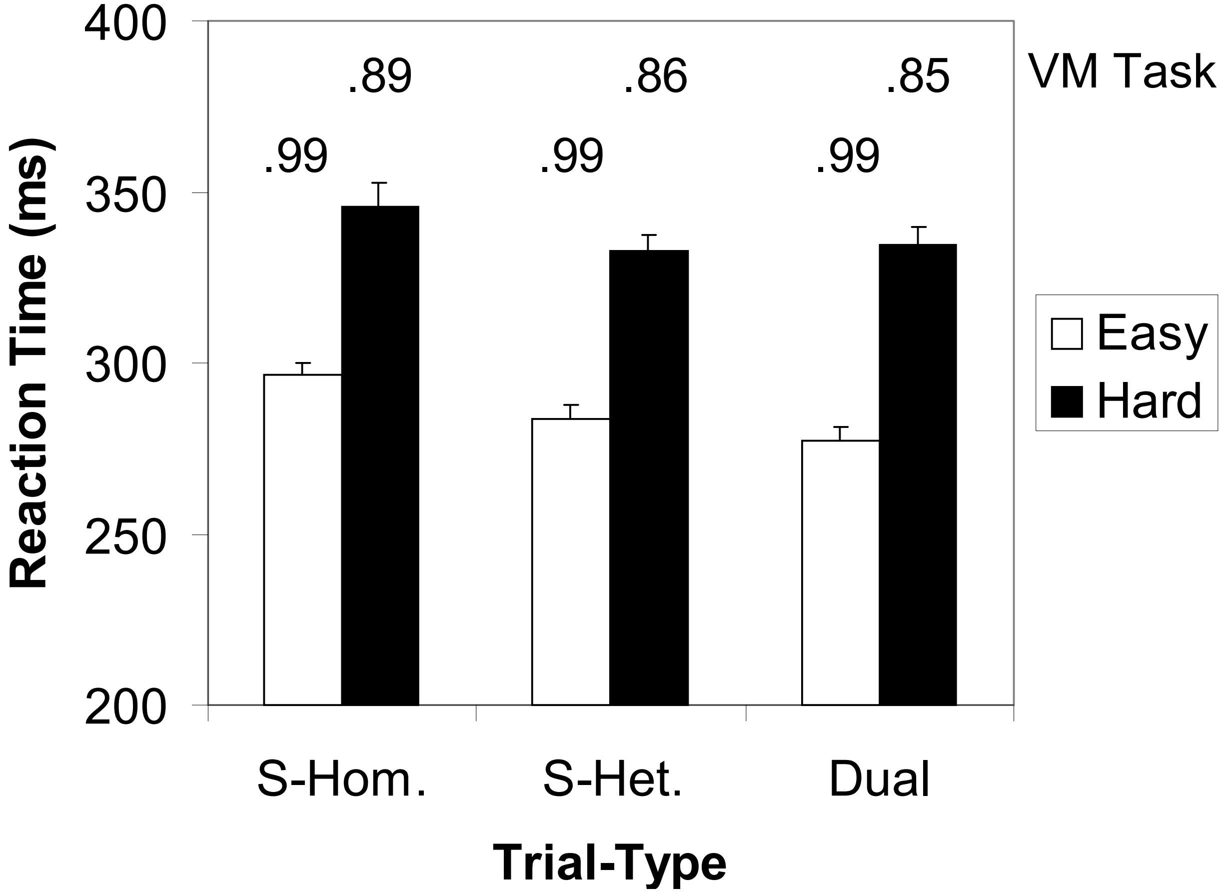
5. Note that even if mapping costs were attributed to pre-bottleneck processes, the costs for the two tasks should be equivalent.

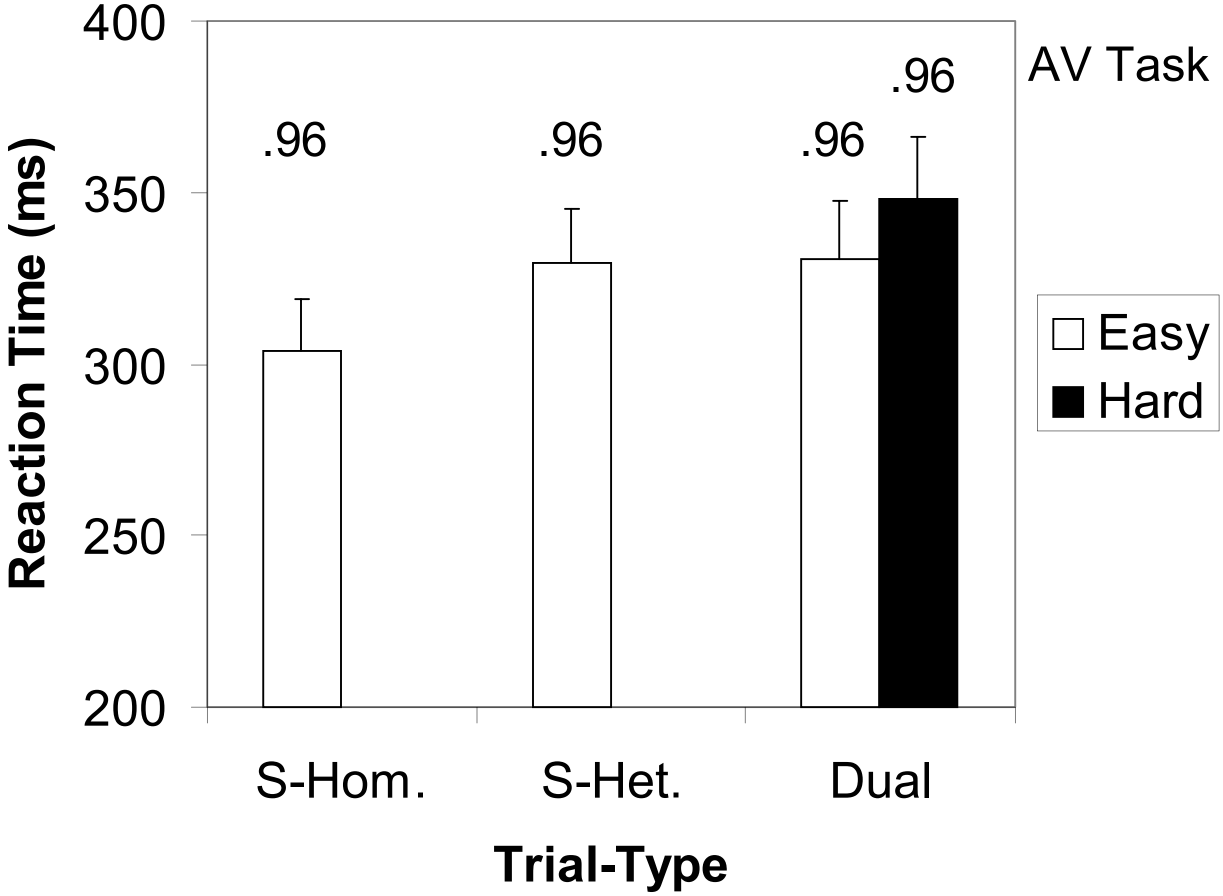
6. We thank Hal Pashler for this suggestion.

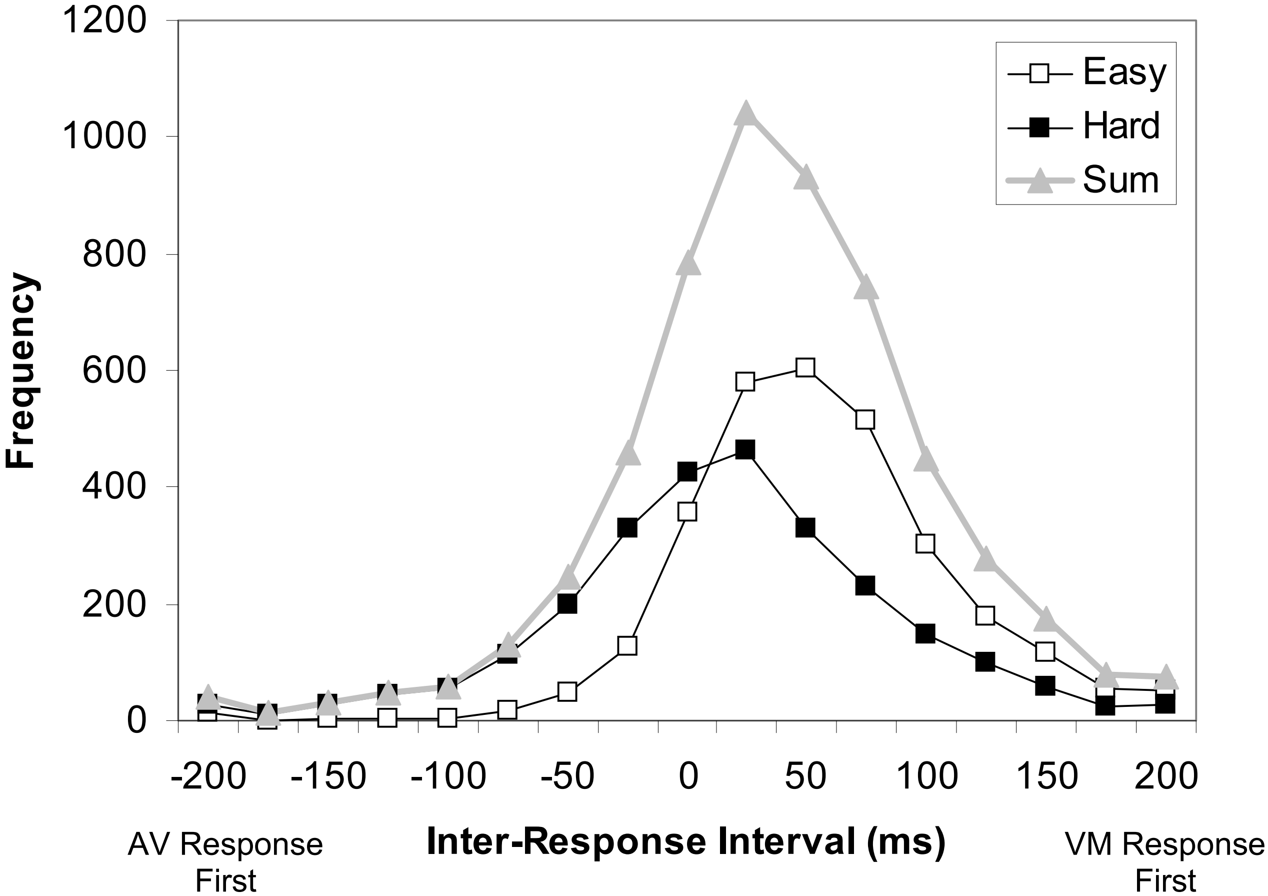

400
350
300
250
200
Reaction Time (ms)
S-Het
D-Old
D-New
.91
.95
.94
.93
.95
.96
.95
.93
O
N
VM
AV
Task

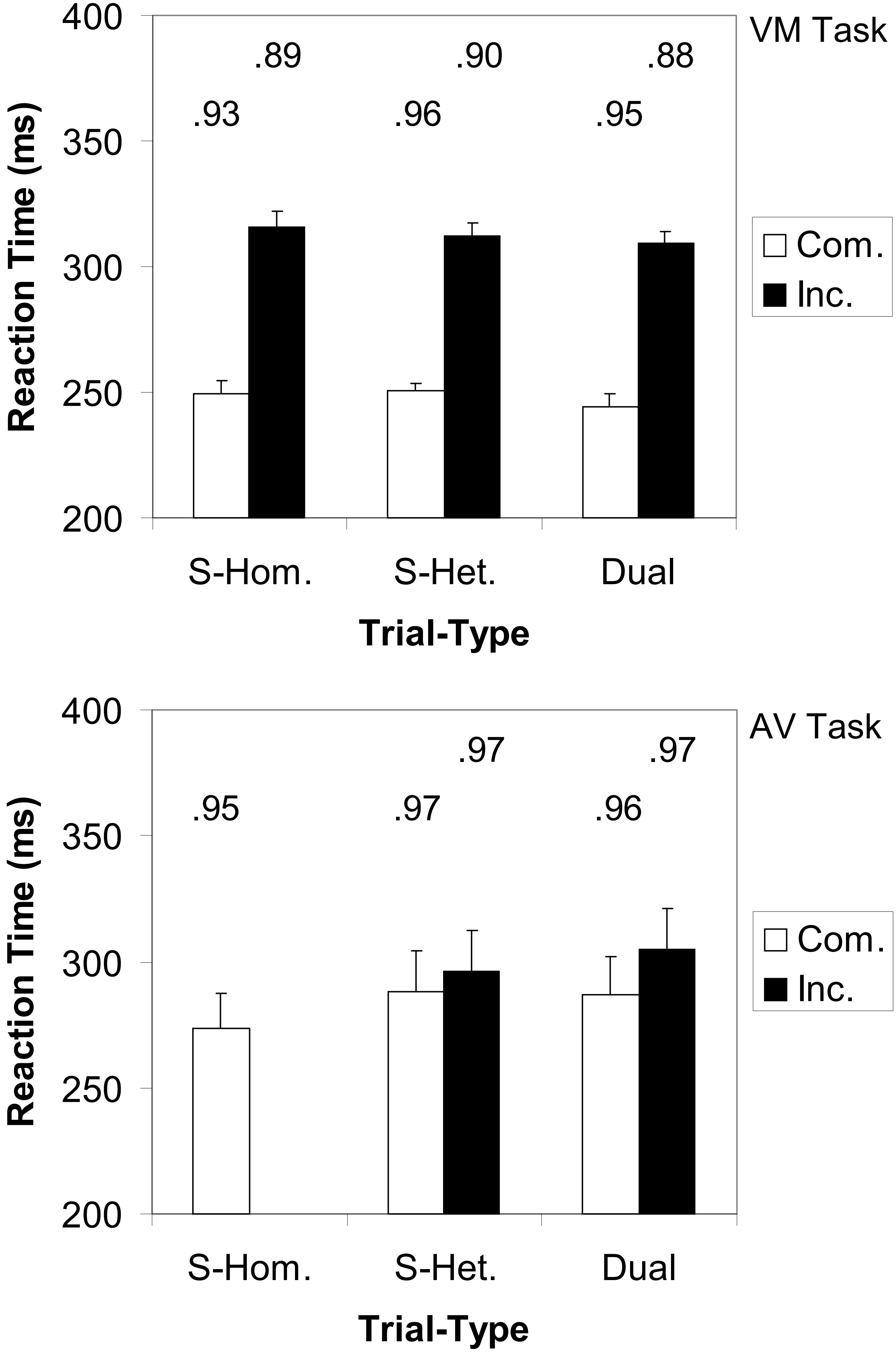

500
450
400
350
300
250
Reaction Time (ms)
Aud. Dual
Aud. S-Het.
Aud. S-Hom.
Vis. Dual
Vis. S-Het.
Vis. S-Hom.
Early
Late
Test
Period

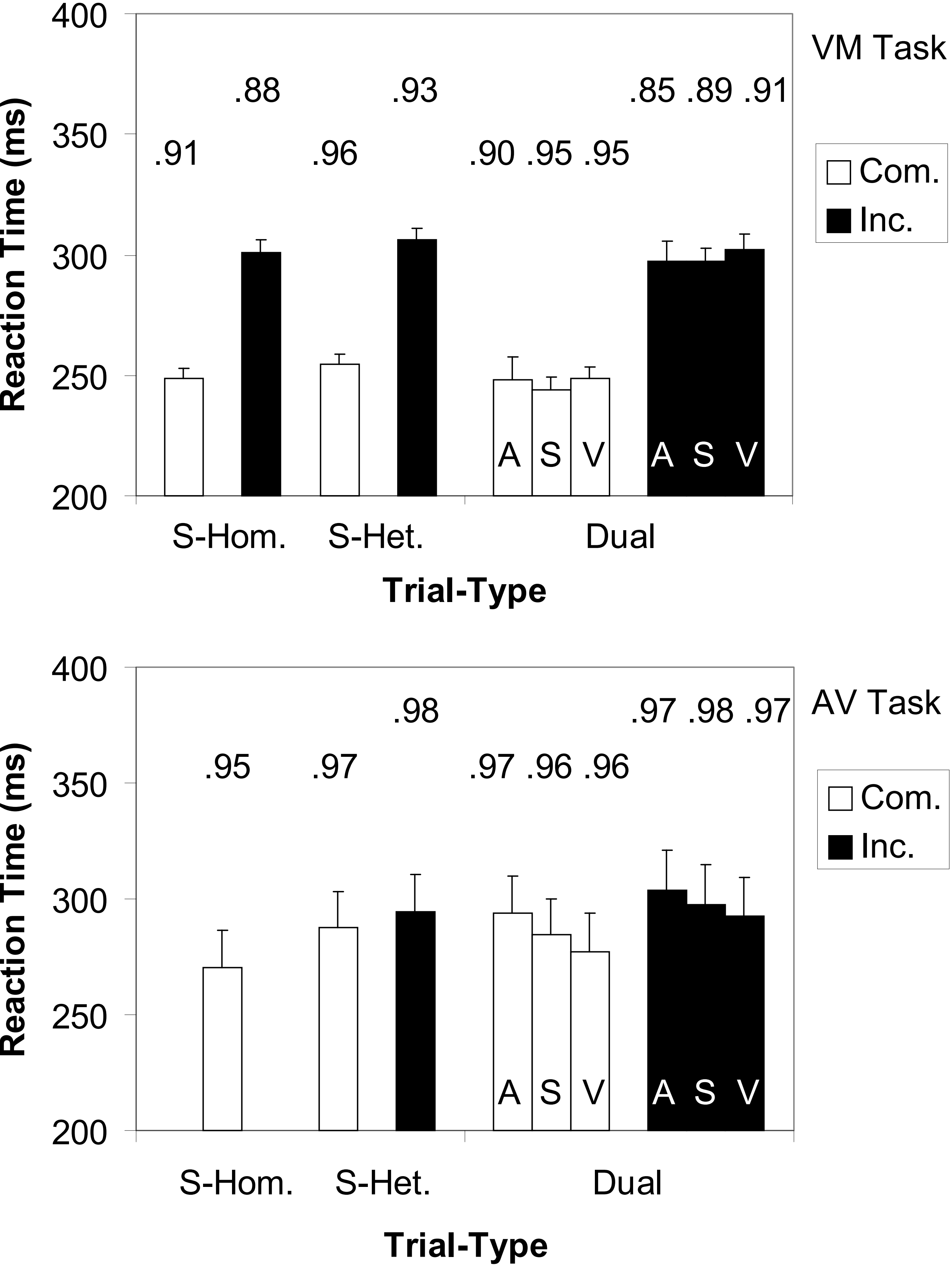

A. No dual-task cost due to non-overlapping selection.
V. Stimulus Classification
V. Resp. Selection
V. Response Execution
A. Stimulus Classification
A. Resp. Selection
A. Response Execution
B. Long classification, short selection.
Hard V. Stimulus Classification
V. Resp. Selection
V. Response Execution
A. Stimulus Classification
A. Resp. Selection
A. Response Execution
C. Short auditory classification, combined selection.
Hard V. Stimulus Classification
Compound Response Selection
V. Response Execution
A. Stimulus Classification
A. Response Execution
D. Long auditory classification, combined selection.
Hard V. Stimulus Classification
Compound Response Selection
V. Response Execution
A. Stimulus Classification
A. Response Execution

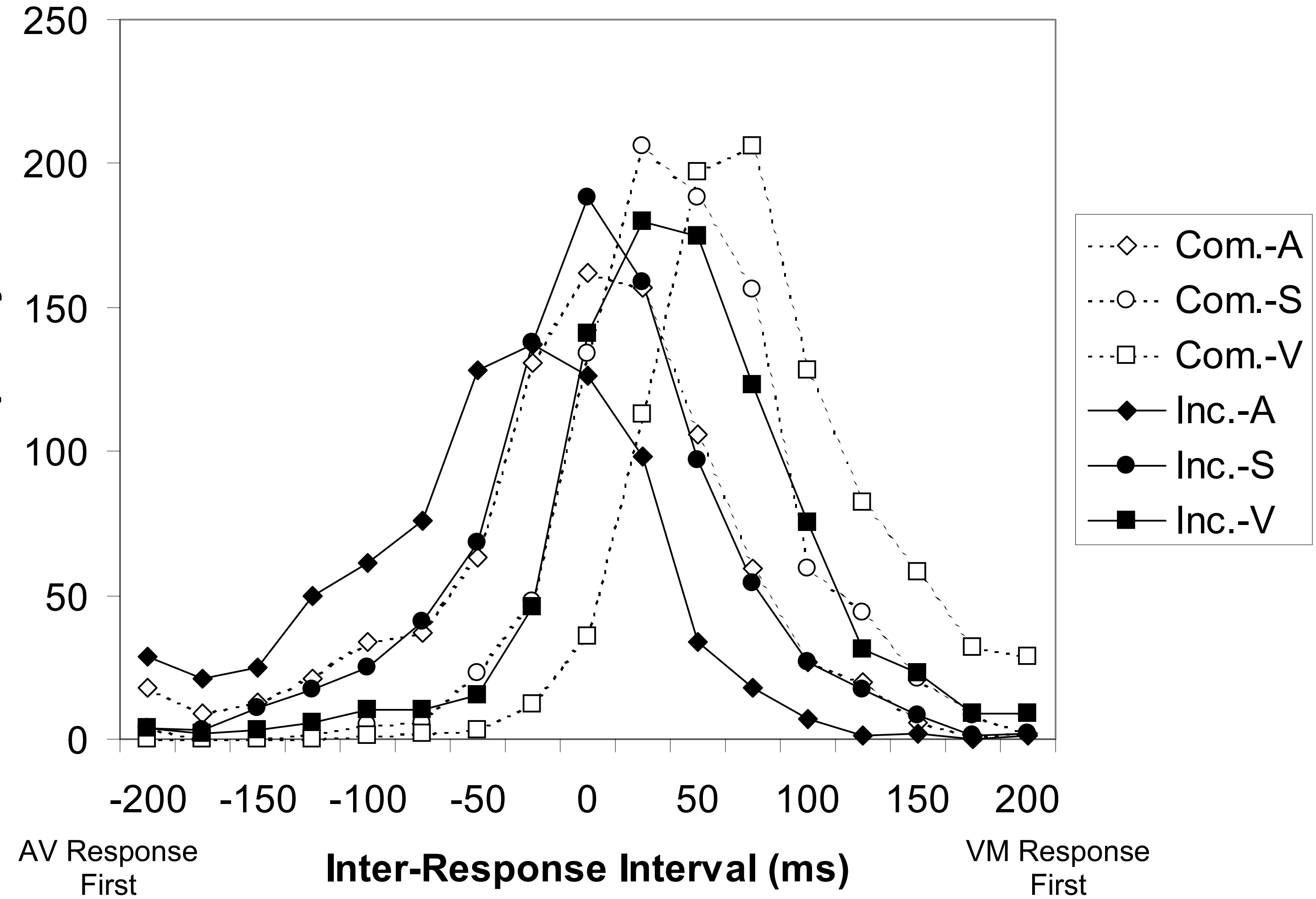

400
350
300
250
200
Reaction Time (ms)
.89
.86
.85
.99
.99
.99
VM Task
Easy
Hard
S-Hom.
S-Het.
Dual
Trial-Type


400
350
300
250
200
Reaction Time (ms)
.96
.96
.96
.96
AV Task
Easy
Hard
S-Hom.
S-Het.
Dual
Trial-Type

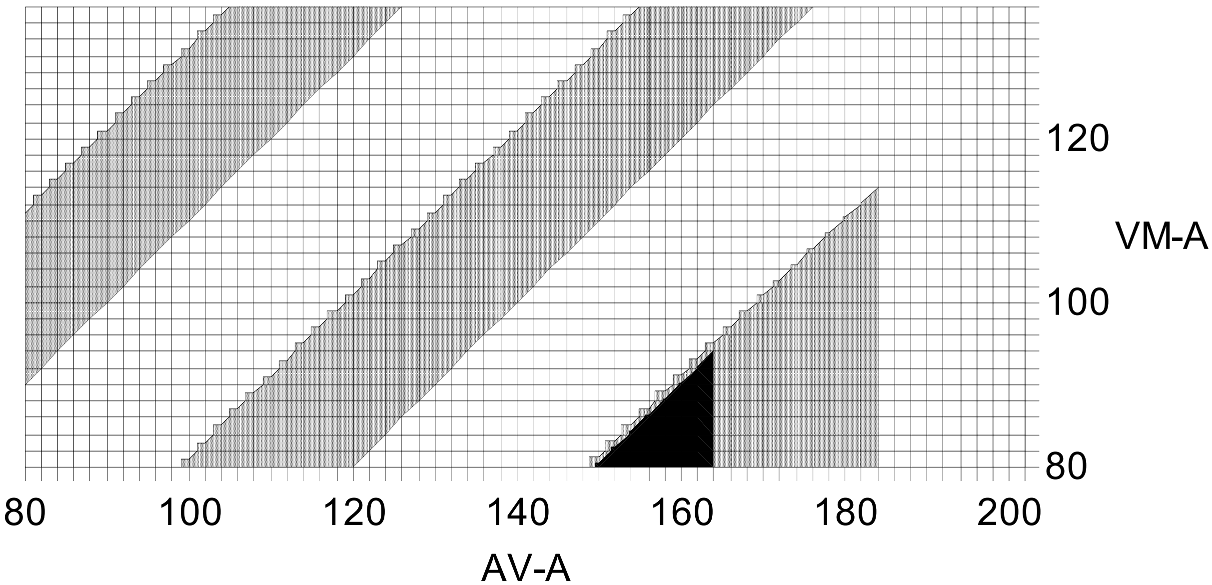

1200
1000
800
600
400
200
0
Frequency
Easy
Hard
Sum
-200
-150
-100
-50
0
50
100
150
200
AV Response First
Inter-Response Interval (ms)
VM Response First

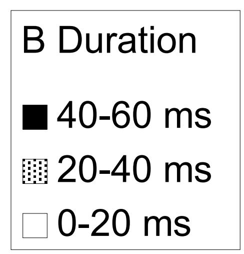

VM Task
.89
.90
.88
.93
.96
.95
Com.
Inc.
Reaction Time (ms)
400
350
300
250
200
S-Hom.
S-Het.
Dual
Trial-Type
AV Task
.97
.97
.95
.97
.96
Com.
Inc.
Reaction Time (ms)
400
350
300
250
200
S-Hom.
S-Het.
Dual
Trial-Type


400
350
300
250
200
Reaction Time (ms)
VM Task
.91
.88
.96
.93
.90 .95 .95
.85 .89 .91
Com.
Inc.
A S V
A S V
S-Hom.
S-Het.
Dual
Trial-Type
400
350
300
250
200
Reaction Time (ms)
AV Task
.95
.97
.98
.97 .96 .96
.97 .98 .97
Com.
Inc.
A S V
A S V
S-Hom.
S-Het.
Dual
Trial-Type


250
200
150
100
50
0
-200
-150
-100
-50
0
50
100
150
200
Com.-A
Com.-S
Com.-V
Inc.-A
Inc.-S
Inc.-V
AV Response First
Inter-Response Interval (ms)
VM Response First

VM-B = 30 ms





AV-B = 30 ms