General Article

VIRTUALLY PERFECT TIME SHARING IN DUAL-TASK PERFORMANCE: Uncorking the Central Cognitive Bottleneck

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A fundamental issue for psychological science concerns the extent to which people can simultaneously perform two perceptual-motor tasks. Some theorists have hypothesized that such dual-task performance is severely and persistently constrained by a central cognitive "bottleneck," whereas others have hypothesized that skilled procedural decision making and response selection for two or more tasks can proceed at the same time under adaptive executive control. The three experiments reported here support this latter hypothesis. Their results show that after relatively modest amounts of practice, at least some participants achieve virtually perfect time sharing in the dual-task performance of basic choice reaction tasks. The results also show that observed interference between tasks can be modulated by instructions about differential task priorities and personal preferences for daring (concurrent) or cautious (successive) scheduling of tasks. Given this outcome, future research should investigate exactly when and how such sophisticated skills in dual-task performance are acquired.

To what extent can two or more tasks that involve perceptual-motor and cognitive processes be performed simultaneously? Answering this question is important for understanding the nature of component mechanisms in human information processing (Meyer & Kieras, 1999). The answer is also relevant for facilitating dual-task performance in practical situations such as driving an automobile while using a cellular telephone (Kieras & Meyer, 1997). Yet serious controversies exist about what people's mental capacities and limitations really are.

For example, some theorists have hypothesized that there is a central cognitive decision and response-selection bottleneck (RSB) whose limited capacity severely and persistently constrains dual-task performance (Pashler, 1994; Welford, 1952). According to this *RSB hypothesis*, if a person is engaged in selecting the response to a stimulus for one task, then selecting another response to a different stimulus for a second task cannot proceed until the first response-selection process has finished. This unavoidable postponement supposedly delays responding to secondary-task stimuli when they occur soon after primary-task stimuli. Putative evidence of such dual-task interference has come from the *psychological refractory period* (PRP) procedure, in which participants perform two choice reaction tasks while giving higher priority to one task and lower priority to the other. Based on this procedure, it has been claimed:

> The results . . . imply surprisingly severe and stubborn limits on what mental activities people can accomplish at the same time. This interference—usually termed the *psychological refractory period effect*—is sizable and robust . . . . It has been observed that thousands of trials of practice do not generally abolish the interference . . . . The problem is cognitive, not motoric . . . . It is commonly supposed, by psychologists and laypersons alike, that [after] activities have become 'automatized' through practice, [they cease] to require 'mental capacity' . . . but the results that do exist suggest that when it comes to selecting responses, practice does not readily eliminate the fundamental bottleneck. (Pashler, 1992, p. 44–48)

In contrast, alternative assumptions about the capacities of human information processing have been made as part of

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adaptive executive control (AEC) models for dual-task performance (Meyer & Kieras, 1997a, 1997b, 1999; Meyer et al., 1995). These models of skilled performance use procedural knowledge in the form of condition-action production rules. Sets of such rules for performing individual tasks are presumably acquired through practice during which declarative knowledge (i.e., verbal descriptions about task requirements) is converted to procedural knowledge (Anderson, 1982; Bovair & Kieras, 1991). According to AEC models, after this conversion has been completed, processes for performing two tasks simultaneously—including response selection—may be executed in parallel by a cognitive processor. Furthermore, dual-task performance may then be supervised through executive control that manages peripheral perceptual-motor resources and satisfies prevailing task priorities. Concomitantly, dual-task interference could stem from at least two distinct sources: (a) incomplete conversion of declarative to procedural knowledge and (b) conservative executive control that optionally postpones some stages of one task while another task is under way. Nevertheless, given the assumptions of AEC models, it should be possible to perform some choice reaction tasks simultaneously with little or no dual-task interference after the conversion from declarative to procedural knowledge has been completed.

This article reports three experiments whose results confirm the latter possibilities. We reach several related conclusions: (a) After only moderate practice, people can achieve virtually perfect time sharing between two basic choice reaction tasks; (b) when required, conservative executive control may postpone one such task while another is under way, yielding dual-task interference despite the potential for virtually perfect time sharing; and (c) personal preferences for cautious rather than daring task scheduling underlie individual differences in dual-task interference. Our experiments significantly extend previous reports of virtually perfect time sharing (e.g., Allport, Antonis, & Reynolds, 1972; Greenwald & Shulman, 1973; Shaffer, 1975), which have been discounted because they allegedly involved methodological artifacts (cf. McCann & Johnston, 1992; Pashler, 1994; Van Selst, Ruthruff, & Johnston, 1999).

EXPERIMENT 1

To manifest virtually perfect time sharing, our first experiment used auditory-vocal (AV) and visual-manual (VM) tasks similar to ones that have yielded high (>200 ms) dual-task interference in the PRP procedure (e.g., McCann & Johnston, 1992; Pashler, 1990; Schumacher et al., 1999). The stimulus and response modalities of these tasks differed so that performing them would not be delayed by competition for limited perceptual-motor resources. This allowed us to localize dual-task interference in central cognitive operations (Meyer & Kieras, 1997a). Eliminating such interference involved giving participants explicit equal-priority task instructions, strong incentives for maximum performance, and moderate amounts of practice.

Method

We tested 8 participants (4 male and 4 female university students) who performed their tasks during various types of trials.[1] On each trial with the AV task, a low (220 Hz), medium (880 Hz), or high (3520 Hz) tone occurred for 40 ms. In response, the participant said “one,” “two,” or “three,” respectively. On each trial with the VM task, two dashes and a capital *O* were displayed in a row at the center of a computer monitor, forming the stimulus O--, -O- , or --O.[2] In response, using the right hand, the participant pressed the key associated with the index, middle, or ring finger, respectively. The reaction time (RT) and accuracy of each response were recorded.

We included *mixed-trial* and *pure-trial* blocks. Each mixed block involved a sequence of *dual-task* and *heterogeneous single-task* trials. On each dual-task trial, three dashes were displayed initially for 500 ms as a warning signal at the center of the computer monitor. Next, two stimuli (a tone and an *O* with two dashes), sampled randomly from their respective ensembles, occurred at the same time. Participants had to perform the two tasks simultaneously with equal priorities. On each heterogeneous single-task trial, after the warning signal, a single stimulus—either auditory or visual—was presented, and only one task had to be performed. Heterogeneous single-task trials were interleaved randomly with dual-task trials; there was a 2-s intertrial interval. This helped ensure that participants were equally prepared for the two tasks throughout the mixed blocks. In contrast, during each pure block, there was a sequence of *homogeneous single-task* trials. Throughout each pure block, just one task—either VM or AV—was performed repeatedly. This helped us assess possible task-specific preparatory effects. Before each trial block, participants were told what type it would be.

For each participant, five experimental sessions were conducted. Session 1 included 12 pure-trial blocks (6 per task). Session 2 included 6 pure blocks (3 per task) and 8 mixed blocks.[3] Sessions 3 through 5 were identical to Session 2 except that they included 10 mixed blocks. Each mixed block had 18 dual-task and 30 heterogeneous single-task trials (15 per task). Each pure block had 45 homogeneous single-task trials. By the end of Session 5, a participant had performed each task on just 2,064 trials. This much practice is far less than the number of trials over which high (>100 ms) dual-task interference reputedly persists in the PRP procedure (cf. Gottsdanker & Stelmach, 1971; Van Selst et al., 1999).

To eliminate such interference, we instructed participants to perform each task quickly and accurately regardless of whatever

1. One female participant who committed more than 15% errors was excluded from subsequent data analyses.

2. Visual stimuli subtended horizontal and vertical visual angles of 0.72° and 0.36°, respectively.

3. The first two blocks of Session 2 were pure (one per task) and the next two were mixed; following these four blocks, each pure block was followed by two mixed blocks.

Table 1. *Mean reaction times and error rates (in parentheses) from Experiments 1 and 3*

Task	Trial type	Session 2	3	4	5	6
		Experiment 1				
Auditory-vocal	Dual task	725 (6.5)	566 (8.0)	507 (6.3)	456 (5.4)	
	Heterogeneous single task	655 (5.3)	539 (7.7)	486 (4.0)	447 (3.3)	
	Homogeneous single task	604 (3.5)	509 (5.2)	475 (2.2)	445 (3.1)	
Visual-manual	Dual task	352 (2.4)	322 (4.0)	300 (3.5)	283 (5.6)	
	Heterogeneous single task	338 (1.3)	310 (2.6)	292 (2.2)	282 (2.7)	
	Homogeneous single task	306 (4.7)	294 (4.9)	287 (4.4)	279 (4.7)	
		Experiment 3				
Auditory-vocal	Dual task	1,178 (6.8)	809 (8.4)	680 (6.0)	621 (5.7)	565 (4.8)
	Heterogeneous single task	821 (2.9)	607 (4.9)	532 (4.5)	493 (2.9)	466 (4.1)
	Homogeneous single task	656 (2.7)	560 (3.6)	515 (3.9)	486 (2.5)	469 (3.4)
Visual-manual	Dual task	965 (10.2)	732 (9.1)	652 (6.8)	572 (6.9)	522 (5.3)
	Heterogeneous single task	778 (6.9)	612 (7.7)	551 (5.6)	492 (7.3)	466 (6.9)
	Homogeneous single task	673 (9.8)	578 (6.1)	533 (4.2)	486 (5.7)	466 (5.4)

Note. Reaction times are in milliseconds. Error rates are percentages.

else happened on a trial, and not to constrain the serial order of their responses. Monetary payoffs were awarded for correct-response RTs on dual-task trials that fell below deadlines defined by the 75th percentiles of RT distributions from prior heterogeneous single-task trials. Payoffs also were given for less-than-deadline RTs on heterogeneous and homogeneous single-task trials. Incorrect responses were penalized.[4] Our reward system differed from those in the standard PRP procedure, in which participants must give higher priority to a primary task and lower priority to a secondary task on each trial.

Results

Table 1 shows results from Experiment 1. Because dual-task trials occurred during Sessions 2 through 5, mean correct-response RTs and error rates from these sessions were assessed for each task with analyses of variance that included session number, trial type, and participant as factors.[5]

VM task

For the VM task, mean RTs declined from Session 2 through 5, $F(3, 18) = 15.1$, $p < .001$. Manual responses tended to be slowest on dual-task trials and fastest on homogeneous single-task trials, $F(2, 12) = 6.32$, $p < .05$. However, over sessions, this trial-type effect decreased, $F(6, 36) = 3.43$, $p < .01$. By Session 5, only 4 $\pm$ 4 ms separated the mean VM RTs on dual-task and homogeneous single-task trials, $t(7) = 0.95$, $p > .10$. This essentially null difference is our first demonstration of virtually perfect time sharing.

Error rates for the VM task were low (3.6%). Homogeneous single-task trials yielded the most errors, and heterogeneous single-task trials the fewest, $F(2, 12) = 7.39$, $p < .01$. However, this effect was small, and the trial-type-by-session interaction was unreliable, $F(6, 36) = 1.27$, $p > .25$. Nor was there a reliable main effect of session, $F(3, 18) = 1.44$, $p > .25$. Together, these results suggest that responses on dual-task trials were not affected much by a trade-off between speed and accuracy.

AV task

Error rates were slightly higher in the AV task than in the VM task, and RTs were substantially longer. Still, the patterns of factor effects were similar for the two tasks.

Mean AV RTs declined from Session 2 through 5, $F(3, 18) = 27.9$, $p < .001$. Vocal responses tended to be slowest on dual-task trials and fastest on homogeneous single-task trials, $F(2, 12) = 7.67$, $p < .01$. However, over sessions, this trial-type effect decreased, $F(6, 36) = 8.57$, $p < .001$. By Session 5, only 11 $\pm$ 10 ms separated the mean AV RTs on dual-task and homogeneous single-task trials, $t(7) = 1.11$, $p > .10$. This essentially null difference is our second demonstration of virtually perfect time sharing.

4. Participants were paid $5 per session, plus bonuses based on their performance. For each correct-response RT less than the prevailing deadline, 100 points were awarded. For each incorrect response, 100 points were deducted. Points were converted to bonuses at a rate of $1 per 20,000 points.

5. Before our analyses of variance, we excluded RT outliers with an algorithm described elsewhere (Schumacher et al., 1999). RT outliers occurred infrequently and haphazardly across trial types and tasks.

Error rates in the AV task did not change reliably over sessions, $F(3, 18) = 2.45$, $p > .05$. Dual-task trials yielded the most errors, and homogeneous single-task trials the fewest, $F(2, 12) = 8.02$, $p < .01$. However, this effect was small, and the accompanying trial-type-by-session interaction was unreliable, $F(6, 36) = 0.89$, $p > .5$. Differences in error rates across trial types remained about the same from Session 2 through Session 5, again suggesting that responses on dual-task trials were not affected much by a trade-off between speed and accuracy.

Discussion

Our initial results suggest that dual-task performance is not persistently limited by a central cognitive bottleneck. If such a bottleneck had played a major role in this experiment, then throughout dual-task trials, mean RTs for the AV task, VM task, or both should have exceeded mean RTs on single-task trials by 100 ms or more, but such enduring interference failed to occur. After less than 2,000 trials per task, we found virtually perfect time sharing, contrary to the RSB hypothesis. Instead, this finding supports AEC models, which assume that people have sufficient cognitive capacity to execute concurrent procedures for two basic choice reaction tasks at the same rates as for a single task (Meyer & Kieras, 1997a, 1997b, 1999).

Confronted with such evidence, proponents of the RSB hypothesis (e.g., McCann & Johnston, 1992; Pashler, 1994; Van Selst et al., 1999) might offer post hoc explanations to discount our results, extending their criticisms of previous reports about virtually perfect time sharing (e.g., Allport et al., 1972; Greenwald & Shulman, 1973). Perhaps the VM task of Experiment 1 was special in that on dual-task trials, the selection of responses for this task finished before response selection for the AV task began. It is even conceivable that the VM task required no cognitive response selection, because our visual stimuli and manual responses were spatially compatible, which might let perceptual codes be translated directly into motor codes through a "privileged loop" that bypasses the "central" RSB (cf. McLeod & Posner, 1984). If so, then our demonstration of virtually perfect time sharing could be artifactual. The relatively short RTs for Experiment 1's VM task are consistent with this possibility. Thus, we conducted two more experiments to test these alternate hypotheses.

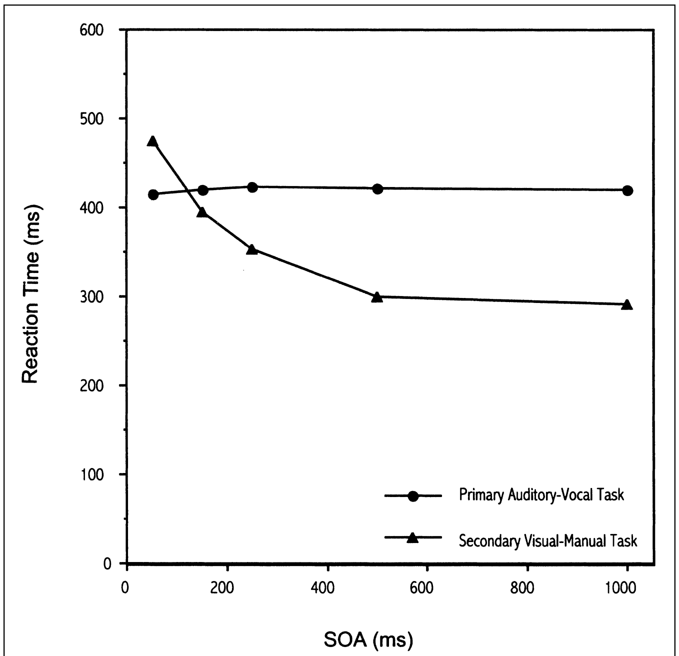

Fig. 1. Mean reaction times for the primary auditory-vocal and secondary visual-manual tasks at each stimulus onset asynchrony (SOA) during Experiment 2, which used the psychological refractory period procedure.

EXPERIMENT 2

The purpose of Experiment 2 was to show that in at least some crucial respects, the VM task of Experiment 1 has no special status and, like other basic choice reaction tasks, may yield dual-task interference during the PRP procedure. With this experiment, we show that such interference may stem from conservative adaptive executive control rather than an immutable limited-capacity RSB.

Method

Another test session was run with dual-task trials involving the AV and VM tasks of Experiment 1. The participants were the same as before, but the temporal arrangement of stimuli and the instructions about task priorities were changed to conform with those of the PRP procedure (e.g., Pashler, 1984; Pashler & Johnston, 1989). On each trial, the stimulus for the VM task followed the stimulus for the AV task by a variable stimulus onset asynchrony (SOA) of 50, 150, 250, 500, or 1,000 ms. We instructed participants that they should respond quickly and accurately to each stimulus, but that they should treat the AV task as primary, and that their responses for it should always occur before responses for the secondary VM task. Feedback and rewards, like those in Schumacher et al. (1999), strongly encouraged compliance with these unequal-priority instructions. Each participant received 14 dual-task trial blocks with 45 trials per block, and the various SOAs occurred equally often.

Results

Figure 1 shows mean correct-response RTs plotted across SOAs. Regardless of SOA, the primary AV task yielded RTs that approximately equaled those in Session 5 of Experiment 1. Corresponding error rates were low (2.4%) and not affected reliably by SOA, $F(4, 24) = 0.63$, $p > .5$. At the longest SOA, mean RTs for the secondary VM task also approximately equaled those in Session 5 of Experiment 1. However, as the SOA decreased, sec-

Table 2. *Mean reaction times and error rates (in parentheses) averaged across the two tasks for the participant subgroups of Experiment 3*

		Session				
Subgroup	Trial type	2	3	4	5	6
High interference	Dual task	1,189 (10.0)	915 (11.0)	809 (4.9)	761 (6.0)	693 (5.1)
	Heterogeneous single task	872 (6.6)	702 (6.6)	603 (4.2)	558 (3.8)	522 (3.9)
	Homogeneous single task	712 (7.4)	630 (3.9)	544 (3.6)	535 (3.9)	528 (3.9)
Moderate interference	Dual task	1,002 (8.0)	725 (8.9)	578 (9.0)	535 (8.1)	479 (6.7)
	Heterogeneous single task	675 (6.2)	530 (7.4)	480 (7.8)	450 (7.5)	428 (9.8)
	Homogeneous single task	562 (7.7)	507 (9.1)	481 (5.2)	453 (7.0)	425 (6.1)
Low interference	Dual task	1,006 (7.4)	674 (7.0)	587 (6.6)	490 (5.8)	451 (4.4)
	Heterogeneous single task	792 (3.1)	567 (5.6)	517 (4.7)	459 (5.2)	437 (5.1)
	Homogeneous single task	667 (4.8)	545 (3.9)	525 (4.0)	461 (3.2)	437 (4.3)

Note. Reaction times are in milliseconds. Error rates are percentages.

ondary-task RTs increased, manifesting high dual-task interference at the shortest SOA, $F(4, 24) = 25.7$, $p < .001$. Corresponding error rates likewise increased from 2.6% to 12% as the SOA decreased, $F(4, 24) = 11.7$, $p < .001$.

Discussion

The results of Experiment 2 suggest that the VM task used in Experiment 1 was not especially unusual. Like other basic choice reaction tasks, and unlike tasks that may not require cognitive response selection (e.g., saccades toward a target; Pashler, Carrier, & Hoffman, 1993), the VM task yielded high dual-task interference when performed with secondary priority under the PRP procedure. In turn, this leads us to conclude tentatively that the virtually perfect time sharing found earlier was not an artifact of the tasks used.

Experiment 2 also reveals that the PRP procedure may produce dual-task interference whose source is not an immutable central RSB. Presumably no such bottleneck caused the present interference, because if it had, then dual-task interference also should have persisted throughout Experiment 1. Instead, slowing of secondary-task responses may be mediated by adaptive executive control that schedules task processes appropriately to obey instructions about their relative priorities and serial order, as suggested by AEC models (Meyer & Kieras, 1999).

EXPERIMENT 3

With Experiment 3, we answer another key question. Do some people time-share almost perfectly when they perform an AV task along with a VM task that involves less compatible stimulus-response associations and longer RTs than in Experiment 1? While providing an affirmative answer, Experiment 3 also demonstrates that individual differences in dual-task interference may emerge as practice progresses. This further supports AEC models, which claim that executive control incorporates personal preferences for cautious or daring task scheduling (Meyer et al., 1995; Meyer & Kieras, 1999).

Method

We tested 11 new participants (5 male and 6 female university students) during six sessions. Trial blocks, trial types, instructions, feedback, and payoffs were designed as in Experiment 1. The AV task remained the same, but the VM task involved spatially incompatible stimulus-response associations, which increased the difficulty of response selection (Duncan, 1977; Fitts & Seeger, 1953). On each trial with this task, three dashes and a capital *O* were displayed in a row at the center of the computer monitor, forming the stimulus O---, -O--, --O- , or ---O. In response, with the right hand, the participant pressed the key associated with the ring, index, little, or middle finger, respectively.

Results

Table 1 shows mean correct-response RTs and error rates for each task and trial type. The data were analyzed as in Experiment 1.

VM task

Unlike in Experiment 1, mean RTs for the VM task were approximately as long as those for the AV task. The VM task yielded decreasing RTs over sessions, $F(4, 40) = 36.9$, $p < .001$. Manual responses tended to be slowest on dual-task trials and fastest on homogeneous single-task trials, $F(2, 20) = 16.0$, $p < .001$. However, over sessions, there was a reliable decrease in this trial-type effect, $F(8, 80) = 8.44$, $p < .001$. By Session 6, some participants time-shared almost perfectly for the VM and AV tasks, whereas others again manifested considerable dual-task interference, as we discuss in detail later (cf. Table 2).

Mean error rates were slightly higher for the VM task than for the AV task. The main effects of session and trial type in the VM task were not reliable, $F(4, 40) = 1.80$, $p > .10$, and $F(2, 20) = 2.89$, $p > .05$, respectively; neither was the interaction of these two factors, $F(8, 80) = 0.89$, $p > .5$. However, differences in error

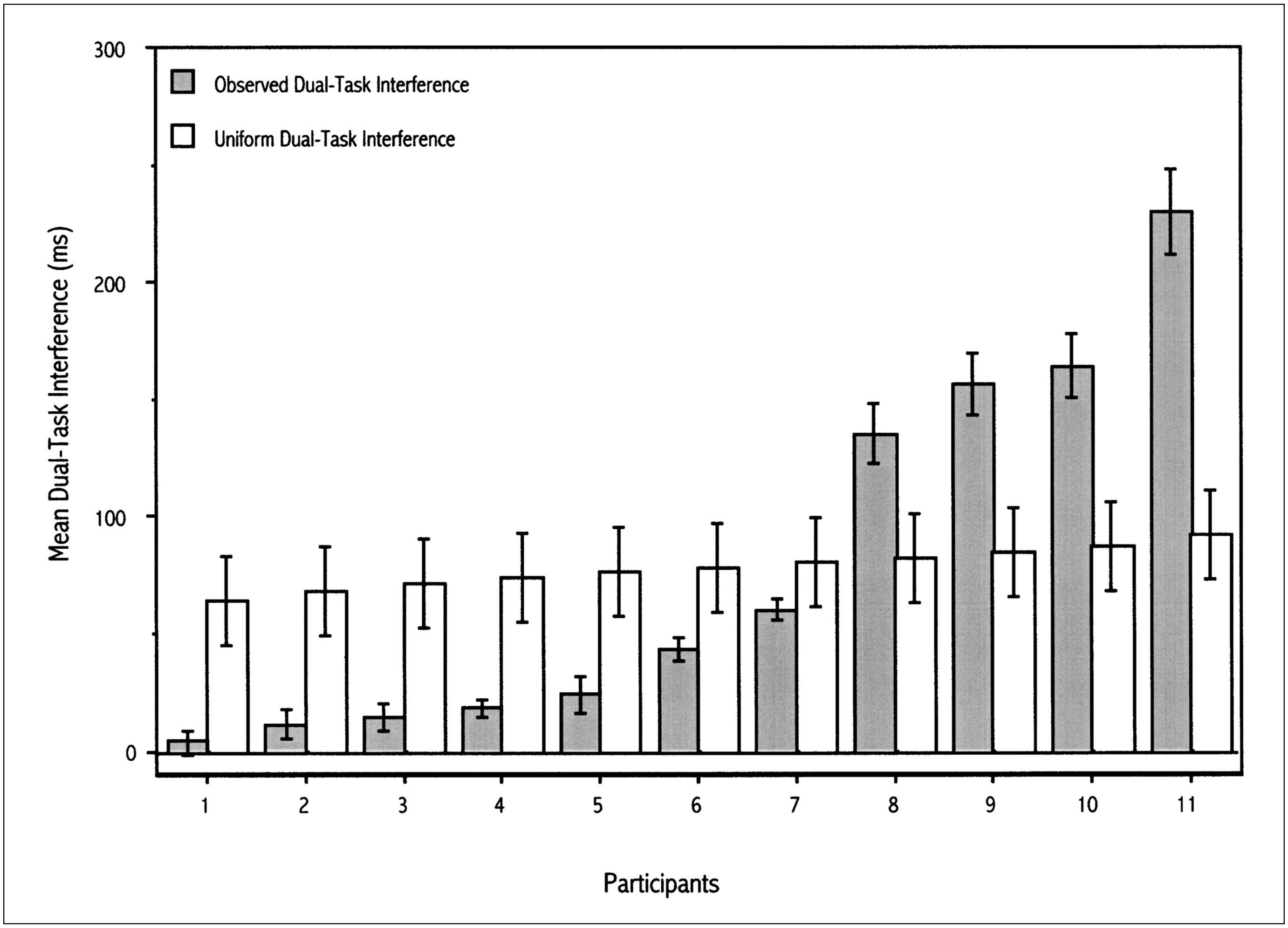

Fig. 2. Observed (dark bars) and expected uniform (light bars) amounts of dual-task interference in Session 6, rank-ordered from smallest to largest for the 11 participants in Experiment 3. The short vertical lines with tick marks show 95% confidence intervals based on random trial-by-trial variability of individual reaction times within each participant.

rates across trial types tended to decrease from Session 2 through Session 6, again suggesting that responses on dual-task trials were not affected much by a trade-off between speed and accuracy.

AV task

For the AV task, mean RTs declined from Session 2 through Session 6, $F(4, 40) = 59.9$, $p < .001$. Vocal responses tended to be slowest on dual-task trials and fastest on homogeneous single-task trials, $F(2, 20) = 49.4$, $p < .001$. However, over sessions, this trial-type effect decreased, $F(8, 80) = 33.2$, $p < .001$. By Session 6, some participants time-shared almost perfectly for the AV task, whereas others still manifested considerable dual-task interference (cf. Table 2).

Error rates for the AV task were low. They changed unreliably over sessions, $F(4, 40) = 1.08$, $p > .30$. Dual-task trials yielded the most errors, and homogeneous single-task trials the fewest, $F(2, 20) = 19.1$, $p < .001$. However, this effect was small. Although the trial-type-by-session interaction was unreliable, $F(8, 80) = 1.43$, $p > .15$, differences in error rates across trial types tended to decrease from Session 2 through Session 6, suggesting that responses on dual-task trials were not affected much by a trade-off between speed and accuracy.

Individual differences

Furthermore, some systematic individual differences in dual-task performance emerged during Experiment 3. For example, Figure 2 (dark bars) shows the observed amount of interference (difference between mean RTs on dual-task and heterogeneous single-task trials) for each participant in Session 6. Also shown in Figure 2 (light bars) are corresponding uniform amounts of interference that would be expected on the basis of three assumptions: (a) Task processes and task scheduling were the same across participants; (b) all participants had the same true mean dual-task interference; and (c) observed amounts of interference differed between participants only because of random trial-to-trial variability in their RTs. If these assumptions were veridical, then the observed and expected uniform amounts of interference should have been approximately equal. However, for most individual participants, the observed amount of interference was either reliably higher or reliably lower than the expected uniform amount. This is consistent with our AEC models (Meyer et al., 1995; Meyer & Kieras, 1997b, 1999), under which participants may use a variety of task-scheduling strategies (e.g., a cautious one with minimal temporal overlap in processing for the two tasks, or a daring strategy with a great deal of processing overlap) during the course of practice, and so exhibit various amounts of dual-task interference.

A hierarchical clustering analysis (Ward, 1963) revealed that participants formed three distinct subgroups. In one subgroup (Participants 8, 9, 10, and 11), interference remained extremely high during Session 6 (consistent with the use of a cautious scheduling strategy), whereas a second subgroup (Participants 6 and 7) had moderate interference, and a third subgroup (Participants 1, 2, 3, 4, and 5) had extremely low interference (consistent with the use of a daring scheduling strategy). Within the third subgroup, narrow 95% confidence intervals around the observed amounts of interference either included or came close to 0 ms, qualifying these participants as virtually perfect time sharers.

Table 2 shows some characteristics in performance that may have mediated these differences between subgroups. During Session 2, the high-interference subgroup had longer mean RTs and higher error rates than did the low-interference group, even on homogeneous single-task trials, which required no time sharing. The moderate-interference subgroup had the shortest mean RTs on both homogeneous and heterogeneous single-task trials during Session 2, but their error rates were about the same as those of the high-interference group, and their mean RT on dual-task trials was about the same as that of the low-interference group. By Session 6, error rates of the high-interference group decreased to about the same level as those of the low-interference group, but their mean RTs remained relatively long even on homogeneous single-task trials, whereas error rates of the moderate-interference group remained relatively high.[6] Thus, it appears on balance that even initially, the low-interference group had the greatest propensity toward perfect time sharing, and they may have benefited especially from dual-task practice because they performed relatively well with respect to both response speed and accuracy (Kieras, Meyer, Ballas, & Lauber, 2000).

6. Across participants, the correlation between amount of dual-task interference and mean RT on homogeneous single-task trials of Session 6 was highly positive ($r = .81$, $p < .01$).

Discussion

Experiment 3 shows that virtually perfect time sharing is more than just an artifact of combining a special easy VM task with a more difficult AV task. Even when such tasks are about equally difficult, some participants learn to time-share almost perfectly in performing them. This ability cannot be explained by a central cognitive bottleneck whose low capacity persistently and severely slows dual-task performance. Instead, it seems more likely that concurrent response-selection processes and adaptive executive control of dual-task performance are readily feasible, as expected from our prior AEC models (Meyer & Kieras, 1997b, 1999; Meyer et al., 1995).

GENERAL DISCUSSION

Although the present experiments show that many participants may achieve virtually perfect time sharing for at least some representative AV and VM tasks, our results also raise a number of interesting new questions. What mechanisms enable task processes and executive control to change during dual-task practice? Why do some but not all people readily achieve virtually perfect time sharing? Would practice eventually enable everyone to time-share perfectly? Can special training regimens promote this perfection? Although it is impossible to address these questions completely here, we can point the way toward the answers.

According to our theoretical framework, skill in dual-task performance is acquired through several stages (Kieras et al., 2000). Transitions between them are presumably made by learning algorithms that take the quality of current performance into account. This may lead from initially inefficient performance based on declarative task knowledge to ultimately efficient performance based on synthesized procedural knowledge. Along the way, each stage would have its own style of executive control, manners of interaction between task processes, and uses of context-dependent information. Consequently, the extent to which dual-task interference remains after some practice could depend systematically on people's tendencies to respond slowly or inaccurately, as Experiment 3 revealed. In turn, such dependencies might be related to inherent abilities, as well as personality traits like impulsivity-reflectivity (Dickman & Meyer, 1988). An exciting agenda for future research will be to develop these ideas about dual-task performance and adaptive executive control more fully.

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