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Success and Failure at Dual-Task Coordination by Younger and Older Adults

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Dual-task processing was explored in younger and older adults in 2 experiments that used a tone discrimination and a letter discrimination task. To encourage parallel processing if that was possible, the authors presented the stimuli for the 2 tasks simultaneously, and participants were instructed to withhold their responses until both were ready. The authors found no evidence for parallel processing and no evidence that the management of central processing of dual tasks is qualitatively different in older adults than it is in younger adults. When one response was verbal and the other manual, the 2 responses closely coincided. When both responses were manual, the authors did find that the first response was not delayed enough to coincide with the 2nd and that this underestimation was greater in older adults.

Keywords: cognitive aging; dual-task interference; response-selection bottleneck; parallel processing

Performance of two overlapping tasks appears in many circumstances to be limited by a bottleneck in which response selection can occur for only one task at a time (for a review, see Pashler, 1994). This has been interpreted as the result of a central structural limitation (Pashler, 1998; Pashler & Johnston, 1989; Welford, 1952). An alternative view is that the bottleneck is voluntary and strategic. In this view, individuals choose to impose the bottleneck because of demand characteristics of the situation, including the facts that the imperative stimuli for the two tasks are often presented sequentially and that the instructions may seem to call for responding to one task before the other or for emphasizing one task over the other (Meyer & Kieras, 1997a, 1997b). Meyer, Glass, Mueller, Seymour, and Kieras (2001) have argued that processing of two tasks can be simultaneous under the right circumstances.

Ruthruff, Pashler, and Klaasen (2001) devised a procedure to eliminate or at least attenuate noncentral sources of task interference—peripheral interference, voluntary postponement, and preparation changes—to encourage parallel processing if that was possible. They presented individuals with two tasks, but the stimuli appeared simultaneously. One task was to indicate whether one or two tones were played (to which a vocal response was given); the other was to indicate whether a rotated letter was in normal or mirror image form (to which a manual response was given). Because the two tasks used different input and output modalities, this procedure should have largely eliminated peripheral interference. Not only were the individuals instructed to weight the two tasks equally, but also they were instructed to withhold their responses until both tasks were completed and then to give the responses simultaneously. Ruthruff et al. (2001) reasoned that if processing of the two tasks could be carried out simultaneously, then this procedure should certainly encourage it, largely eliminating any demand characteristics for voluntary postponement. In addition, the procedure encourages the individual to prepare for both tasks in advance of the simultaneous appearance of both stimuli, rather than delaying preparation for a later appearing stimulus. If a bottleneck was present that allowed response selection for only one task at a time, however, then it should still be possible to detect the operation of the bottleneck by varying the difficulty of response selection in one of the tasks, as we explain in the next paragraph. The difficulty of the tone task was increased by requiring that the individual respond “2” when one tone was heard and “1” when two tones were heard rather than the natural mapping of the response “1” to one tone and “2” to two tones in the easier version of the task.

There are two principal sets of predictions of a response-selection bottleneck model, illustrated in Figure 1B. First, the latency of the dual-task responses should be much longer than the latency of the response to either task in a single-task situation. In the dual-task situation, response selection for one task must be suspended until response selection in the other task is completed, resulting in a bottleneck delay. In contrast, a parallel-processing model in Figure 1C shows that the dual-task responses should be emitted at about the same latency as the slower of the two single tasks. The second prediction is that, comparing situations with the harder tone task to those with the easier tone task, the slowing in the dual-task responses should be identical to the difference between the hard-tone single task and the easy-tone single task (shown as a shaded area labeled *Tone Effect* in Figure 1). That is, the slowing of response selection in the more difficult tone task should propagate to the dual-task responses. Again by contrast, the parallel-processing model would predict that all or part of the

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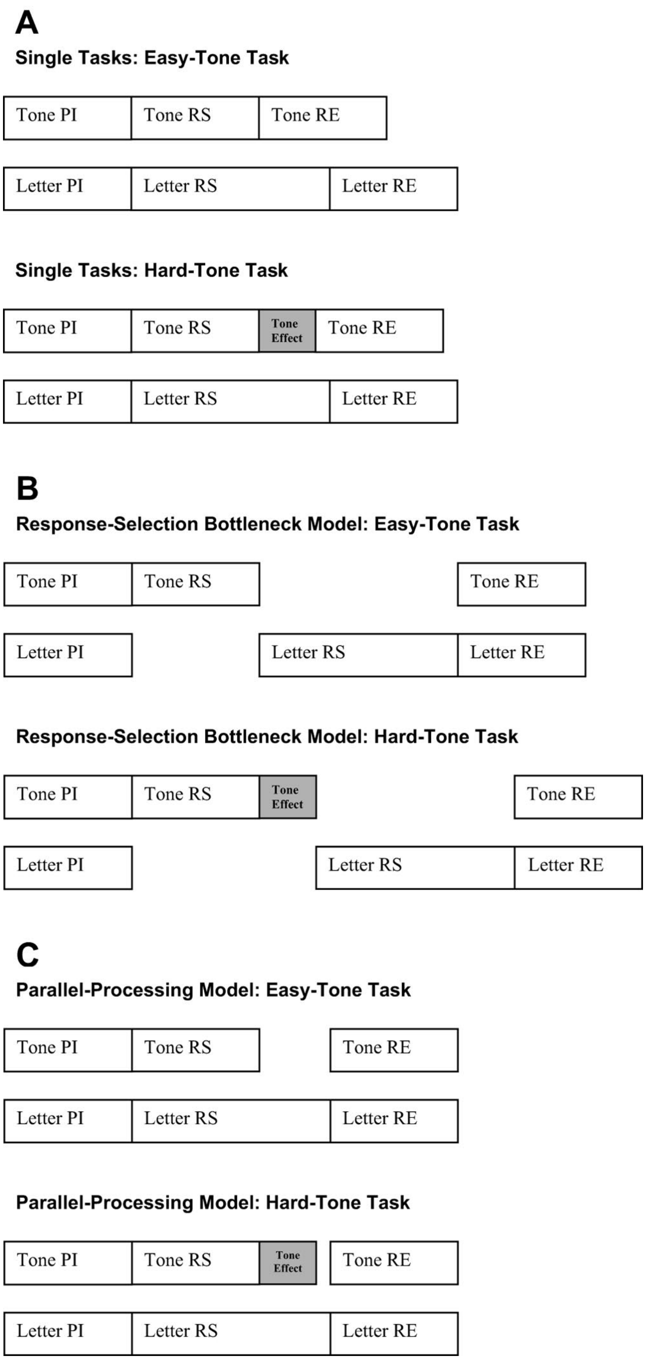

Figure 1. Processing time diagrams: A: Single-task condition. B: Dual-task condition according to a response-selection bottleneck model. C: Dual-task condition according to a parallel-processing model. PI = perceptual identification; RS = response selection; RE = response execution.

processing time added by the increase in tone-task difficulty should be absorbed into the bottleneck delay or "slack" time when response selection has finished in one task but not the other to the extent that the delay caused by the increased tone-task difficulty did not exceed the bottleneck delay.

The results of Ruthruff et al. (2001) were completely consistent with the existence of a response-selection bottleneck. Furthermore in control experiments, they demonstrated that the results could not have been because of special costs imposed by the instruction to group. The estimated slowing due to response grouping was not significantly different from zero. Moreover, response-grouping costs should not be affected by task difficulty; therefore, they cannot account for the propagation of tone-task difficulty that was observed. Further, when the instruction to group was removed, there was still strong evidence for the presence of a bottleneck. Their results do not show, and they do not claim, that parallel processing cannot occur under any circumstances. Rather the results show that parallel processing does not occur even when situational demands are completely compatible with it. Recent evidence and arguments bear on the question of the circumstances under which parallel processing may be observed, and we return to that question in the General Discussion section.

Age-Related Differences in Dual-Task Interference

It has been argued that older adults perform more poorly in dual-task situations than do younger adults (e.g., McDowd & Shaw, 2000). Formal meta-analyses have shown that there are significant dual-task costs, which may (Hartley, 1992) or may not (Chen, 2000) be slightly larger in older adults. Salthouse (e.g., 1996) noted that almost all response latencies increase with age, and as a result, difference measures such as those between dual and single task would also be expected to increase proportionately. He argued that all or virtually all of the age-related differences in dual-task costs could be explained as artifacts of general age-related slowing (Salthouse & Miles, 2002). Verhaeghen, Steitz, Sliwinski, and Cerella (2003), however, showed in a meta-analysis that dual-task costs were slightly but detectably larger in older adults, even when general slowing had been taken into account.

Most of the studies included in the meta-analyses have used procedures with little control over the relative onset of processing in the two tasks. For example, McDowd and Craik (1988) gave 24-s episodes in which individuals responded to 12 auditory reaction-time (RT) trials and 15 visual RT trials. The analysis was based on mean RT in each task and did not explore the effects of the relative onset times for the two stimulus sets. More recent age-group comparisons have adopted variants of the psychological refractory-period procedure (Vince, 1948; Welford, 1952), in which the amount of potential interference between the two tasks is systematically manipulated by varying the delay of the onset of the second task after the first task from very small values (e.g., 50 ms)—presumed to produce high interference—to very large values (e.g., 1,500 ms)—presumed to produce little or no interference. By fitting models such as those described above (e.g., Meyer & Kieras, 1997a, 1997b; Pashler, 1998; Ruthruff et al., 2001), it has been possible to draw more focused conclusions about aspects of dual-task processing that might differ between younger and older adults. The results for older adults, as for younger adults, have been well fit by response-selection bottleneck models. Allen, Smith, Vires-Collins, and Sperry (1998) concluded that interference in response selection between the two tasks was greater in older than in younger adults. Glass et al. (2000) and Hartley and Little (1999), however, concluded that after general slowing was taken into account, the age differences were small, and they could be localized to greater difficulty in perceptual registration and to a longer lag between the completion of response selection in the first task and the "unlocking" of processing in the second task. Maquestiaux, Hartley, and Bertsch (2004) also implicated greater difficulty of task switching when they found that highly trained older adults—but not younger adults—were aided by shifting to tasks that were comparable but with simpler response-selection rules. Hartley (2001) showed that much of the age difference in task switching could be eliminated when the responses to the two tasks were in different modalities. In contrast, Hein and Schubert (2004) concluded that older adults were more sensitive to interference in input modalities.

What has not been examined is the performance of older adults when the two tasks are presented simultaneously, with inputs and outputs in different modalities, with instructions giving equal emphasis to the two tasks, and with responses allowed in any order. If the standard psychological refractory-period procedures encourage voluntary strategic postponement of processing of the stimulus for the second task, then prior results could have misestimated the true differences in interference between younger and older adults. If voluntary postponement is more likely or more persistent in younger adults, then the true age difference in central interference may be greater than has been found. If voluntary postponement is more likely or more persistent in older adults, then the true difference may be less than has been found. Glass et al. (2000) concluded that older adults were less likely than younger adults to adopt a daring strategy in which processing of the two tasks could overlap, therefore findings of greater dual-task interference may indeed reflect greater voluntary postponement in older adults.

Experiment 1

Method

Participants

Twenty-four younger adults (M = 19.9 years, SD = 1.0 years, 18 women) and 23 older adults (M = 78.4 years, SD = 5.5 years, 15 women) participated in the experiment. The younger adults were college students who participated in return for extra course credit; the older adults were volunteers from the local community who participated in return for a stipend of $15. Younger adults reported 12.5 years of education (SD = 0.7); older adults reported 17.0 years of education (SD = 3.6).[1] Younger adults gave a mean self-rating of health of 8.2 (SD = 1.2); older adults gave a mean self-rating of health of 8.2 (SD = 1.4). Mean visual acuity for younger adults was 20/18.3 (SD = 4.1); for older adults, mean visual acuity was 20/31.2 (SD = 15.3).[2]

Tasks

Single tasks. In the single-task blocks, each trial began with a fixation point—an asterisk—in black centered on the white display and presented for 500 ms. The fixation was followed either by one or two tones or by a letter. The tone stimuli were either one 800-Hz tone, 15 ms in duration, or two such tones separated by 50 ms, presented over headphones. Participants responded to the tone by speaking into a microphone mounted on a loose-fitting collar and positioned near the lips. In the easy-tone task, they were asked to say "one" if they heard one tone and "two" if they heard two tones. In the hard-tone task, they were asked to say "one" if they heard two tones and "two" if they heard one. Responses were accepted for 5,000 ms. The letters were A, B, C, and D. Responses to the letters were given by pressing labeled buttons on the keyboard, with the *U* key (labeled C) mapped to the index finger of the right hand, the *I* key (labeled A) mapped to the second finger, the *O* key (labeled D) mapped to the third finger, and the *P* key (labeled B) mapped to the little finger. The letters subtended approximately 3.2° vertically by 2.4° horizontally at an approximate viewing distance of 46 cm. The letter was present for 5,000 ms or until a response was given. There was a 500-ms intertrial interval.

Dual tasks. Each dual-task trial began with an asterisk fixation point presented for 500 ms. Then the tones—one or two—and the letter—A, B, C, or D—were presented simultaneously. The participant was instructed to withhold the responses until both were ready and then to give them both at exactly the same time. Responses were accepted for up to 5,000 ms after the stimuli were presented. As in the single task, there were easy and hard versions of the tone task. The mapping of letters to finger responses was as in the single tasks. There was a 500-ms intertrial interval.

Procedure

There were 16 practice trials followed by three blocks of 32 experimental trials in each of the four conditions—easy single task, easy dual task, hard single task, hard dual task—for a total of 384 experimental trials. Accuracy feedback was provided during the practice but not the experimental trials. Half of the participants completed the easy tasks followed by the hard tasks; the other half of the participants completed the hard tasks followed by the easy tasks. The single-task blocks always preceded the dual-task blocks at a particular difficulty level. Visual acuity and color vision were tested, and personal information was collected at the end of the experiment.

Results

Analyses of RTs are based on single-task trials for which the responses were correct and dual-task trials for which both responses were correct. RTs were generally longer for the older adults. As a result, rather than establish arbitrary cutoffs for unusually long and short RTs and then trim those trials, we elected to find the median RT in each condition for each participant. Because there were a substantial number of trials in each condition, the use of medians eliminated the effect of outliers without distorting the measure of central tendency. Descriptive statistics for the tone and letter responses in single- and dual-task situations are given in Table 1. Significance was set at .05 for all tests.

The parallel-processing model and the response-selection bottleneck model made quite different predictions about the relative RTs for the two tasks. The parallel-processing model predicted that

[1] The younger adults were largely first- and second-year college students. Prior cohorts from this population have later reported a mode of 18 years of education. This would make them comparable to the older sample in this study. We noted that this is a particularly well-educated group of older adults.

[2] We did not formally assess auditory acuity. We adopted an a priori criterion that accuracy on the single-tone task had to be 95% or higher. No one was excluded with this criterion.

Table 1
Descriptive Statistics for Tone and Letter Single-Task and Dual-Task Reaction Times (RTs; in ms) in Easy- and Hard-Tone Conditions in Experiment 1

	Age group			
	Younger		Older	
Variable	*M*	*SE*	*M*	*SE*
	Easy-tone condition			
Single task				
Tone RT	752	42	890	30
Letter RT	869	28	1,201	36
Dual task				
Tone RT	1,286	44	1,701	51
Letter RT	1,266	47	1,677	51
	Hard-tone condition			
Single task				
Tone RT	855	36	1,119	38
Letter RT	858	25	1,228	42
Dual task				
Tone RT	1,411	54	1,948	72
Letter RT	1,396	56	1,929	72

the average RT for the first of the two responses given on dual-task trials should occur at about the same time as the slowest of the average RTs on the single-task trials. The response-selection bottleneck model predicted that the fastest dual-task response would come substantially later than the slowest single-task response. To test these predictions, we determined the first response emitted on each dual-task trial and obtained the median of those RTs for each participant. The slowest single-task response was determined by comparing the medians for the tone single task and the letter single task. An analysis of variance (ANOVA) was carried out with age group and type of response (fastest dual-task response and slowest single-task response) for the easy-tone task. Descriptive statistics are given in Table 2. The central result was that there was a significant interaction of Age Group × Task, $F(1, 45) = 9.38$, $p = .004$ (partial $\eta^2 = .17$), with an average difference between fastest dual-task and slowest single-task response of 406 ms for younger adults and 517 ms for older adults.

The parallel-processing model predicted that the increase in difficulty from the easy to the hard tone-task response mapping would be partially, if not completely, absorbed by the cognitive slack available between the time the faster tone task was completed and the time the slower letter task was completed. The response-selection bottleneck model predicted that the increased time to process the hard-tone task would be propagated, lengthening the fastest dual-task response by an equivalent amount. To test these predictions, we estimated a tone effect for each participant by finding the difference between the single-task tone RT with the hard mapping and with the easy mapping. To determine whether processing was delayed or not, we calculated an absorption-propagation effect as the difference between the fastest dual-task response with the hard-tone response mapping and the fastest dual-task response with the easy-tone response mapping. Descriptive statistics are given in Table 3. ANOVA of the two effects showed only a significant effect of age group, with the average tone effect longer for older adults (M = 229 ms in Table 3, SE = 34 ms) than for younger adults (M = 103 ms, SE = 48 ms), $F(1, 45) = 5.08$, $p = .03$ (partial $\eta^2 = .10$). Specifically, the mean absorption-propagation effect (M = 196 ms, SE = 31 ms) did not differ from the mean tone effect (M = 166 ms, SE = 30 ms), $F(1, 45) = 0.83$ (partial $\eta^2 = .02$). (The mean difference in the effects was 40 ms for younger adults and 20 ms for older adults.)

If the respondents were able and willing to follow the directions, then the interresponse interval should have been small, approaching zero. The interresponse interval was determined on each trial for each participant by finding the absolute difference in the RT to the tone and the RT to the letter. As with the original RTs, to reduce the impact of outlier trials with extremely long interresponse intervals but without setting an arbitrary cutoff, the median interresponse interval was determined for each participant in each condition. Participants were able to group their responses and emit them at the same time. The mean of the median interresponse intervals was 25 ms (SE = 1 ms) and was affected only by the difficulty of the tone task, $F(1, 45) = 7.59$, $p = .008$ (partial $\eta^2 = .14$). The effect was slight: RTs were 3 ms longer with the harder tone task (M = 26 ms, SE = 1 ms) than with the easier tone task (M = 23 ms, SE = 1 ms). Interresponse intervals for younger adults (M = 25 ms, SE = 2 ms) and for older adults (M = 24 ms, SE = 2 ms) were virtually identical.

Although neither model predicted which response would be given first, we might expect that the order of finish would vary from trial to trial. Nevertheless, the letter task was consistently favored. The tone-task difficulty did affect the order in which the responses were given, with the letter response given first a significantly greater proportion of the time with the hard-tone task (M = 0.82, SE = 0.02) than with the easy-tone task (M = 0.77, SE = 0.02), $F(1, 45) = 7.10$, $p = .011$ (partial $\eta^2 = .14$). There were no significant effects of age group.

Table 2
Descriptive Statistics for Slowest Single-Task and Fastest Dual-Task Reaction Times (in ms) in Easy- and Hard-Tone Conditions in Experiment 1

	Easy tone				Hard tone			
	Slowest single		Fastest dual		Slowest single		Fastest dual	
Age group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Younger	892	39	1,298	45	913	32	1,441	57
Older	1,201	35	1,718	46	1,269	36	1,967	57

Table 3
Tone Effect (Hard-Tone Single-Task Reaction Time [RT] − Easy-Tone Single Task RT) and Absorption-Propagation Effect (Hard-Tone Dual RT − Easy-Tone Dual RT) in Experiment 1 (in ms)

	Tone effect		Absorption-propagation effect	
Age group	*M*	*SD*	*M*	*SD*
Younger	103	48	143	39
Older	229	36	249	48

Discussion

The results of Experiment 1 for both younger and older adults are completely consistent with those of Ruthruff et al. (2001) for young adults and with the response-selection bottleneck model they proposed in which the simultaneous responses must be delayed while response selection is carried out in one task and then processing is shifted to response selection in the other task. The fastest dual-task response was substantially slower than the slowest single-task response. The increased time necessitated by carrying out the more difficult response selection in the hard-tone task appeared to be reflected in a comparable lengthening of the time before the first dual-task response was given in both age groups. Finally, participants were able to carry out the instruction to group their responses. With respect to aging, the important conclusion is that in a situation that should have encouraged simultaneous processing of the two tasks—a daring strategy in the terminology of Glass et al. (2000)—neither younger nor older adults gave any evidence of that. Both behaved as though there had been a response-selection bottleneck.

The tone effect provides an estimate of the lengthening of central processing in the harder version of the tone task relative to the easier version. For younger adults, response latencies were lengthened by 13.7% in the harder tone task whereas for older adults, they were lengthened by 25.7%. This difference was not significant, $t(45) = 1.20$, $p = .23$. The absorption-propagation effect provides an estimate of the additional central postponement in the harder version of the tone task. The differences between the tone effects and absorption-propagation effects were small, as predicted. It is most important to note that they were as small as or smaller in older adults than in younger adults. Therefore, to the extent that older adults were slowed in the central processing of the harder tone task, that additional time was propagated to the delay in processing the letter task. Thus, Experiment 1 indicates that central interference between the two tasks was equivalent in older and in younger adults.

Experiment 2

Hartley (2001) concluded that older adults are more affected by output interference than are younger adults in the psychological refractory-period procedure. To explore the possibility of greater interference by using simultaneous presentation procedures, we replicated Experiment 1 with only one change: Both tasks now required a manual response. In Experiment 1, we asked whether either younger or older adults showed evidence that they could bypass the bottleneck (they did not). In Experiment 2, we asked whether the bottleneck might be exacerbated, particularly for older adults, by requiring similar motor responses to the two tasks, instead of the dissimilar responses in Experiment 1.

Method

The tasks and procedures in Experiment 2 were identical to those in Experiment 1 except that participants responded to the tone task with a keypress. In the easy version of the tone task the instructions were to press the *Q* key (labeled "ONE") on the keyboard if one tone was heard and the *W* key (labeled "TWO") if two tones were heard, using the second and index finger of the left hand; in the hard version, the instructions were to press the key labeled "ONE" to two tones and that labeled "TWO" to one tone. Twenty younger adults ($M = 19.7$ years, $SD = 1.0$ years, 13 women) and 19 older adults ($M = 77.2$ years, $SD = 5.6$ years, 11 women) participated. None of them had participated in Experiment 1. The younger adults reported a mean of 12.5 years of education ($SD = 0.9$); the older adults reported 17.5 years of education ($SD = 2.6$). Younger adults gave a mean self-rating of health of 7.8 ($SD = 1.2$); older adults gave a mean self-rating of health of 8.3 ($SD = 1.4$). Mean visual acuity for younger adults was 20/17.2 ($SD = 3.6$); for older adults, mean visual acuity was 20/27.3 ($SD = 6.8$).

Results

As in Experiment 1, median RTs on correct trials were determined for each participant in each condition. Descriptive statistics for the median tone and letter responses in single- and dual-task situations are given in Table 4.

Again, the average of the fastest dual-task responses on each trial and the slower of the average RTs for the two single tasks were determined for the easy-tone task. Descriptive statistics are given in Table 5. For younger adults, the fastest dual-task response was 99 ms slower on average than the slowest single task. This difference was significant, $t(19) = 2.93$, $p = .01$. For the older adults, the fastest dual-task response was 65 ms faster on average than the slowest single-task response, $t(18) = -1.20$, $p = .25$. The results for both younger and older adults are quite different from those of Experiment 1, a point we will return to in the *Discussion* section.

Tone effects and absorption-propagation effects were also calculated as in Experiment 1. The descriptive statistics are given in Table 6. For the younger adults, the tone effect was 159 ms greater than the absorption-propagation effect, a significant difference, $t(19) = 3.09$, $p = .005$. For the older adults, the mean difference

Table 4
Descriptive Statistics for Tone and Letter Single-Task and Dual-Task Reaction Times (RTs; in ms) in Easy- and Hard-Tone Conditions in Experiment 2

	Age group			
	Younger		Older	
Variable	*M*	*SE*	*M*	*SE*
Easy-tone condition				
Single task				
Tone RT	789	29	851	23
Letter RT	867	27	1,338	55
Dual task				
Tone RT	1,132	38	1,342	62
Letter RT	998	35	1,303	56
Hard-tone condition				
Single task				
Tone RT	960	29	1,067	28
Letter RT	885	26	1,385	53
Dual task				
Tone RT	1,268	58	1,567	79
Letter RT	1,119	47	1,527	68

Table 5
Descriptive Statistics for Slowest Single-Task and Fastest Dual-Task Reaction Times (in ms) in Easy- and Hard-Tone Conditions in Experiment 2

	Easy tone				Hard tone			
	Slowest single		Fastest dual		Slowest single		Fastest dual	
Age group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Younger	898	39	997	46	978	39	1,009	69
Older	1,339	50	1,274	58	1,392	49	1,323	87

was similar in magnitude (167 ms) but not significant, $t(19) = 1.72$, $p = .10$.

Analysis of the median interresponse intervals across all conditions and groups showed only that interresponse intervals were significantly longer with the harder tone task ($M = 282$ ms, $SE = 46$ ms) than with the easier tone task ($M = 187$ ms, $SE = 22$ ms), $F(1, 37) = 4.43$, $p = .04$ (partial $\eta^2 = .10$). The mean interresponse interval (234 ms) was substantially longer than in Experiment 1 (25 ms).

The average proportion of trials on which the letter task response was given first was 0.82 ($SE = 0.23$). Analysis of the proportion as a function of age group and tone-task difficulty yielded only a significant effect of tone-task difficulty, $F(1, 37) = 5.13$, $p = .029$ (partial $\eta^2 = .12$). Letter responses were more likely to be given first with the easy-tone task ($M = 0.85$, $SE = 0.04$) than with the hard-tone task ($M = 0.78$, $SE = 0.04$).

Discussion

As we noted, the results of Experiment 2 were sharply different from the results of Experiment 1. First, consider just the conditions with the easy-tone task. In Experiment 1, the fastest response times in the dual-task condition were substantially longer than the slowest response times in the single-task condition (a mean difference of 406 ms for younger adults and 517 ms for older adults). In Experiment 2, the differences were much smaller (a mean difference of 99 ms for younger adults) or even reversed (a mean difference of −65 ms for older adults). Nevertheless, there was no indication of parallel processing: The dual-task cost for the tone task—the difference between the response times in the dual- and single-task conditions—in Experiment 2 was substantial (younger adults, $M = 343$ ms; older adults, $M = 491$ ms). These results are consistent with a modified response-selection bottleneck model, shown in Figure 2, in which response selection for the letter task is undertaken first and response selection for the tone task is blocked until the letter response selection is complete. As can be seen in the model, the dual-task cost for the tone task provides an estimate for the duration of response selection in the letter task. Contrary to the instructions to give the responses at the same time, response execution for the letter task must have proceeded as soon as response selection was complete for the older adults, because the response times were no longer than in the single-task condition, and nearly as soon for the younger adults, because the response times were longer but not nearly as much longer as in Experiment 1.

Now consider the conditions with the hard-tone task. As in the easy-tone conditions, the results are consistent with a delay in response selection in the tone task until response selection in the letter task is complete. The letter responses in the dual-task condition were longer for both age groups than those in the single-task condition (234 ms on average for younger adults; 142 ms for older adults). In Figure 2, this is shown as the shaded area letter delay (LD). In order to comply with the instruction to give the two responses at the same time, the LD with the easy-tone task would have to have been equal to the time necessary for response selection in the tone task. It was not. Then, with the hard-tone task, the LD should have been further increased to offset sufficiently the additional time required, the tone effect. The additional cost of the harder tone task, tone effect in Figure 2, can be estimated as the difference between the hard and easy single tone-task response times: 171 ms for younger adults (a 21.7% slowing); 216 ms for older adults (a 25.4% slowing). In comparison to the easy-tone conditions, the dual-task minus single-task difference for the letter task in the hard-tone conditions was 103 ms greater for younger adults and 177 ms greater for older adults. So the dual-task letter responses in the hard-tone condition were lengthened as though to compensate for the increased difficulty. In neither age group,

Table 6
Tone Effect (Hard-Tone Single-Task Reaction Time [RT] − Easy-Tone Single-Task RT) and Absorption-Propagation Effect (Hard-Tone Dual RT − Easy-Tone Dual RT) in Experiment 2 (in ms)

	Tone effect		Absorption-propagation effect	
Age group	*M*	*SE*	*M*	*SE*
Younger	171	30	12	53
Older	216	28	49	69

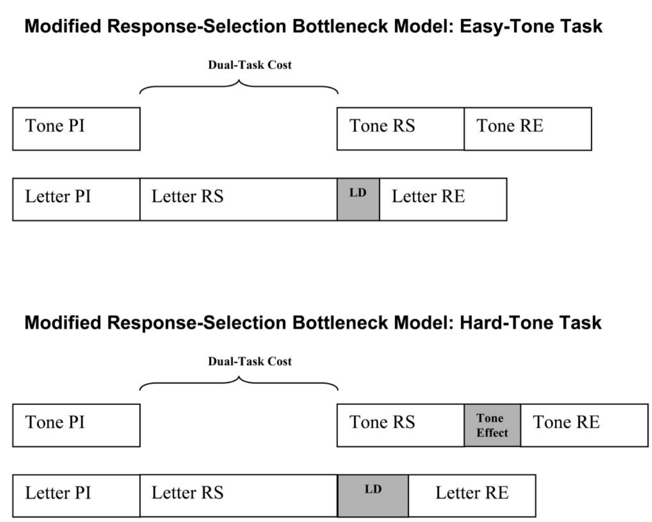

Figure 2. Processing stages in the response-selection bottleneck model, modified to accommodate results of Experiment 2. PI = perceptual identification; RS = response selection; RE = response execution; LD = letter delay.

however, was the lengthening sufficient to offset the longer time required by the more difficult tone task, the tone effect. The younger adults needed to increase the LD by 171 ms but only increased it by 103 ms; the older adults needed to increase the LD by 216 ms but only increased it by 177 ms. The result was that the interresponse interval (196 ms on average for younger adults; 120 ms for older adults) remained similar to what it was in the easy-tone conditions (195 ms on average for younger adults; 150 ms for older adults).

We can infer from the results of Experiment 1 that individuals are able and willing to coordinate their responses to the two tasks under certain circumstances. It seems likely, then, that they were attempting to do so in Experiment 2. The additional delay in the letter-task response with the harder tone task is consistent with this interpretation. When one response is manual but the other response is verbal, individuals are evidently able to estimate accurately when both responses will be ready to emit and how long it will take them to be emitted. This is apparently not true when both responses are manual. The likely explanation for this is that the time necessary to execute the tone response is substantially underestimated and the letter response is not delayed sufficiently. This would mean that in the dual-task context the time to execute a verbal response to the tone task can be estimated accurately, whereas the time to execute a manual response to the same task cannot be estimated accurately. Older adults did not delay the letter response in the easy-tone task at all, therefore in this interpretation the underestimation of the time necessary to prepare the second response is greater for older adults than it is for younger adults. This is plausibly related to the finding that age differences in dual-task interference in the psychological refractory-period procedure are substantially eliminated by requiring responses in different modalities (Hartley, 2001).[3] From Figure 2, we can approximate that the time required for response selection in the letter task—estimated from the dual-task delay in the tone task—is 300 to 500 ms. The misestimation of the point at which processing of the tone task would be complete is not minor, because response execution in the letter task must be released early in the response selection for the tone task, and only shortly after response selection in the letter task is completed. The misestimation is more pronounced for older than for younger adults. Both younger and older adults compensate for the longer time needed to process the hard-tone task than the easy-tone task. Nevertheless, the underlying misestimation remains in both tasks for both age groups.

General Discussion

From an overall perspective, the results of the two experiments provide no evidence of even partial time sharing of response selection in two simultaneously presented tasks either in younger or in older adults. This was true even though the demand characteristics of the situation should have elicited parallel processing if it were possible, unlike the demand characteristics in the conventional psychological refractory-period procedure. The results are consistent with the existence of a response-selection bottleneck. Although we remain agnostic about whether the bottleneck is structural or is strategic and adaptable, our findings add to the body of results in which bottleneck bypass could have been observed but was not.

Parallel dual-task processing, or virtually perfect time sharing, has been reported in other tasks in which simultaneous presentation of the stimuli was used for the two tasks (Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001). It seems clear that it is necessary for one or both of the two tasks to be very simple or to map naturally onto the response (Greenwald, 2003, 2004, 2005; Lien, McCann, Ruthruff, & Proctor, 2005a, 2005b; Lien, Proctor, & Allen, 2002; Lien, Proctor, & Ruthruff, 2003). One interpretation is that any response-selection bottleneck is bypassed in such cases. Three equally viable interpretations are (a) there is bottleneck, but it is of so short a duration as to be undetectable (Hazeltine et al., 2002); (b) the bottleneck only appears to be absent, or merely latent (Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003); or (c) methodological differences between single- and dual-task conditions may have obscured the presence of the bottleneck (Tombu & Jolicoeur, 2004). Another characteristic of procedures that have successfully removed the bottleneck or rendered it undetectable is very extensive practice (see Ruthruff, Hazeltine, & Remington, 2005). The present experiments did not provide extensive practice.

The interesting and unexpected phenomenon was that coordination of response execution in two tasks was possible when the response modalities were different, but it was not possible—either for younger or for older adults—when both responses were in the same modality. We speculate that precise coincidence of speech with other body movements is a well-practiced skill. By contrast, simultaneous motor movements in response to different processing streams are relatively rare. Alternatively, the conflict may arise because of attempts to coordinate activity in sections of left and right motor cortex that control finger movements, sections that are strongly linked through the corpus callosum. If this were the case, the interference might be reduced by using responses more separated on the motor cortex such as hand and foot movements.

From the perspective of aging, the important result is the operation of a response-selection bottleneck of the same nature in older as in younger adults. The demand characteristics that might arguably have produced a greater (or lesser) tendency for a voluntary, strategic bottleneck in older adults in conventional psychological refractory-period procedures were not present here. Nevertheless, there was no evidence that the coordination of response selection in two simultaneous tasks was managed differently or with any less facility by older adults than by younger adults. The underestimation of the delay time for the second manual response in Experiment 2 was greater for older adults, but this was concerned with the requirement for simultaneous responding rather than simultaneous processing. Moreover, the interresponse intervals between a manual and verbal response in Experiment 1 were very small and virtually identical to those of younger adults, implying equally precise response management in the two tasks when the response modalities were different. There simply was no evidence here for an age-related difference in managing the central stages of dual-task processing. This is consistent with findings from previ-

[3] Two other interpretations are that the time necessary to execute the letter response was substantially overestimated and that the instruction was given to execute the two responses at the same time but that there was some structurally imposed delay on the second response. There was no evidence for either of these in Experiment 1.

ous dual-task studies that used the psychological refractory-period procedure that there is little or no qualitative difference between younger and older adults in the central processes of dual-task management (Glass et al., 2000; Hartley, 2001; Hartley & Little, 1999; Hein & Schubert, 2004). It is at odds with the findings of many other dual-task studies that used complex tasks or uncontrolled task scheduling, suggesting that other aspects of those tasks than the specific management of dual tasks were responsible for the age differences that were found.

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