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Age Differences in Dual-Task Interference Are Localized to Response-Generation Processes

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Dual-task differences in younger and older adults were explored by presenting 2 simple tasks, with the onset of the 2nd task relative to the 1st task carefully controlled. The possibility of an age-related reduction in the ability to generate and execute 2 similar motor programs was explored by requiring either a manual response to both tasks or a manual response to the 1st and an oral response to the 2nd and was confirmed by the evidence. The age-related interference was greater than would be expected from a general slowing of processing in older adults. The possibility of an age-related reduction in the capacity to process 2 tasks in the same perceptual input modality was explored by presenting both tasks in the visual modality or the 1st task in the auditory modality and the 2nd task in the visual modality and was not supported by the evidence. There was greater interference when both tasks were in the same modality, but it was equivalent for older and younger adults. Age differences in dual-task interference appear quite localized to response-generation processes.

Age differences in performing two tasks at the same time have been widely sought after (for a recent review, see McDowd & Shaw, 1999). A common assumption is that there is some fundamental resource on which all cognitive operations draw and that this resource is reduced in old age. Dual-task procedures have appeared to provide an ideal test for this assumption. If the resource is more limited in older adults, then a primary task should consume a greater proportion of the available resource, leaving less for a secondary task and resulting in differentially poorer secondary task performance in older adults than in younger adults. The empirical evidence supports the prediction that secondary task performance will be poorer in older adults than in younger adults. A formal meta-analysis of 54 experiments comparing younger and older adults found that age differences in dual-task effects were reliable (Kieley, 1990, described in detail by Hartley, 1992).

Hartley and Little (1999) argued that attributing age differences in dual-task costs, even in well-designed and well-controlled studies, to a reduction in resources is premature. In some studies, both tasks have been complex and have required multiple operations. For example, Salthouse, Rogan, and Prill (1984) presented a list of letters and a list of digits to be recalled, each of which was 75% of the person's maximum span in length. In other studies, the secondary task has been performed continuously. For example, Crossley and Hiscock (1992) had participants alternately tap two keys as quickly as possible while simultaneously performing the primary task. With procedures such as those used by Salthouse et al. and Crossley and Hiscock, there is very little experimental control over the interference between the two tasks; there is no way to know which operations from Task 2 coincide with particular operations from Task 1. Because there are many operations to be carried out, and because the duration of an operation and the ordering of operations may change from trial to trial, aggregate measures could obscure specific sources of dual-task interference. Specific sources of age differences in dual-task interference would appear more general, artifactually implicating an age-related decline in a general resource.

There is an alternative approach, described by Hartley and Little (1999). In this approach, participants carry out two simple, well-learned tasks on each trial. The experimenters control the relative onsets of the stimuli for the two tasks so that the time course of interference can be explored systematically. For example, in some conditions of the present study, each trial began with the presentation of a white X. After 500 ms, the color was changed to blue or yellow. Task 1 was to give a response identifying the color. At some time after the color was changed—a stimulus-onset asynchrony (SOA) of 50, 150, 500, or 1,000 ms—the X was replaced by the letter B or D (the color remained the same). Task 2 was to give a response identifying the letter. Participants were instructed to carry out both tasks as quickly as possible.

This procedure has a number of advantages over other dual-task procedures that have been used in comparing younger and older adults. First, both of the tasks are simple in comparison to, for example, holding in memory two lists that are close to maximum span. They involve relatively few operations, and those operations are likely to be repeated in the same order from trial to trial. On different trials at a particular SOA, then, the operations from the two tasks that are being executed (or are awaiting execution) at a particular point in time should be the same. Second, controlling the SOA should manipulate the interference between the tasks. At very short SOAs, there should be considerable interference between the tasks. At the longest SOA, however, participants will have already

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executed the response to Task 1 before the stimulus for Task 2 is presented. This is a valuable extension to the standard single-task control condition. At long SOAs, participants have done the second task in the dual-task context, although the processing of Task 1 should have been fully completed.

The empirical results with such tasks are well accounted for by a task-switching, or bottleneck, model (for a review of early work, see Bertelson, 1966; for a preliminary statement of the model, see Welford, 1952; for recent reviews, see Pashler, 1993, 1994a, 1998). This model assumes that there is a single response-selection mechanism. Task 2 cannot have access to this mechanism and, thus, cannot proceed with response selection until the mechanism is freed by Task 1. This creates a bottleneck because only one task at a time can have access to the response-selection mechanism. In this model, participants can carry out early perceptual processing in the two tasks in parallel. Similarly, participants can carry out response initiation and execution in Task 1 in parallel with processing in Task 2.

Allen, Smith, Vires-Collins, and Sperry (1998) used serial, dual-task procedures, such as those described, with younger and older adults and obtained results consistent with the task-switching model. Reaction times (RTs) in the second task (T2 RTs) increased as the SOA between Task 1 and Task 2 decreased. RTs in the first task (T1 RTs) were largely unaffected by the SOA. These results are consistent with a model in which response selection can be carried out for only one task at a time. At short SOAs, Task 2 must wait for participants to complete response selection in Task 1. Because Task 1 is already under way before the onset of Task 2, it is not affected by the overlap. Allen et al. found that the increase in T2 RTs at short SOAs was greater for older adults than for younger adults. They interpreted this interaction as evidence for an age-related decrement in attentional time sharing at the response-selection stage of processing. Hartley and Little (1999) extended the task-switching model to incorporate assumptions about age differences. We showed that simply adding a generalized age-related slowing affecting all stages of processing produces a greater increase in T2 RTs at short SOAs for slower processors (e.g., older adults) than for faster processors (e.g., younger adults). There is no need to postulate a specific age-related deficit in carrying out response selection, as Allen et al. had done. In a series of experiments, we showed that the extended task-switching model provided a far better fit to the observed age differences in dual-task performance than did models assuming capacity (or resources) shared between the tasks (and reduced in old age).

We did find (Hartley & Little, 1999) that the interaction of age and SOA in T2 RTs was reliably present when both Task 1 and Task 2 required manual responses (although from different hands); the interaction was reduced or eliminated when Task 1 required a manual response but Task 2 required an oral response. We speculated that there indeed may be a limited capacity for generating and executing highly similar motor responses, and that capacity may be reduced in old age. The present experiment tested that speculation directly by manipulating the similarity of the Task 1 and Task 2 responses—both manual or one, manual, and the other, oral—in a single within-subjects design, rather than in separate experiments. Not only did this provide a replication of the earlier experiment, but it also allowed for a common correction for general slowing across all conditions. We also noted that all of our experiments had presented the information for both tasks in the visual modality (a color judgment and a letter-identity judgment). We could not rule out the possibility of a limited capacity for processing input in one modality or the further possibility of an age-related reduction in that capacity. I tested those possibilities in the present experiment by comparing conditions with both tasks in the visual modality (judging whether an X was blue or yellow and judging whether a letter was B or D) with other conditions in which Task 1 was aural (judging a tone as high or low) and Task 2 was visual.

Method

Participants

Twenty-two younger adults (M = 19.0 years; range = 17–22) and 22 older adults (M = 76.2 years; range = 60–86) participated in the experiment. Younger adults volunteered as one option for receiving extra credit in a psychology course; older adults were recruited from nearby retirement communities and were paid a stipend of $15 for their participation. Younger adults reported 13.1 years of education (SD = 1.2); older adults, 15.6 years (SD = 3.5). On a 10-point scale (10 = *excellent*), younger adults gave a mean self-rating of 8.2 (SD = 1.3); older adults, 8.3 (SD = 1.3). Spatial acuity was measured by obtaining the complete contrast sensitivity function (Vision Contrast Test System; Vistech Consultants, Dayton, OH) and then converting to standard Snellen units. Mean visual acuity for younger adults was 20/18 (SD = 4.0); for older adults, 20/30 (SD = 17.4).

Design and Procedure

There were several training and familiarization tasks: a color-judgment task, a tone-judgment task, a voice-key calibration sequence, and letter-judgment tasks with manual and verbal responses.

Color-judgment task. Participants completed 125 trials on the color task alone. Each trial began with presentation of the letter X in white, centered on the display. After 500 ms, the color was changed to blue or yellow. The participant was instructed to identify the color as quickly as possible by pressing the z key on the keyboard with the middle finger of the left hand for blue or the x key with the index finger of the left hand for yellow. The fingers rested on the keys. Labels (BLUE and YELLOW) were placed just above the keys. The stimulus remained visible either for 1,500 ms or until a response was sensed. The intertrial interval was 1,000 ms. Errors were signaled by a tone. The first 25 trials were identified as practice. Participants were allowed to rest after the practice trials and after 50 experimental trials.

Tone-judgment task. The procedures were almost identical to those of the color-judgment task, except that the discriminant stimulus was a 200-ms tone at either 440 or 990 Hz.

Voice-key calibration sequence. The participant completed a series of 25 trials on which the sensitivity of the headset microphone was adjusted using an ascending staircase method. On each trial, the participant was instructed to say "bee." The final setting was chosen to be sensitive to the individual's voice without being overly sensitive to extraneous noise. The final setting was used for later tasks using the voice key.

Letter-alone tasks. Participants twice completed 125 trials on the letter-alone task, once giving manual responses and again giving oral responses. Each trial began with presentation of the letter X in white, centered on the display. After 500 ms, the X was replaced by a B or D in the same location. After 200 ms, the letter was changed back to X. The participant was instructed to identify the letter as quickly as possible. In the manual task, the response was given by pressing the period key with the index finger of the right hand for B or the slash key with the middle finger of the right hand for D. Labels (B and D) were placed just above the keys. In the oral task, the response was given by speaking the name of the letter into the headset microphone. The stimulus remained visible for 7,500 ms or until a response was sensed. Errors were signaled by a tone. The first 25 trials were identified as practice, and data from those trials were not analyzed. Participants were allowed to rest after the practice trials and after 50 experimental trials.

Dual tasks. There were four versions of the dual task: tone or color discrimination as Task 1, and manual or oral response to the second, letter-identification task. Each trial began with presentation of the letter X in white, centered on the display. For the color discrimination versions, after 500 ms, the color was changed to blue or yellow. The participant was instructed to respond as in the color-alone task. For the tone discrimination versions, after 500 ms, a 440 or 990 Hz tone sounded for 200 ms. At an SOA of 50, 150, 500 or 1,000 ms after the color changed or the tone sounded, the X was replaced by a B or D. The visual stimulus was changed back to a white X, 200 ms after the letter had appeared or the tone sounded. Depending on the condition, the participant was instructed to respond to the letter with either a keypress or a spoken response. The time allowed for a response to the color or tone was 1,500 ms; for the letter, 5,000 ms were allowed. The instructions emphasized responding as quickly as possible to each task. In each of the four versions of the dual task, there were 16 practice trials followed by 192 experimental trials, 48 at each of the four SOAs. Participants were allowed to rest after the practice trials and after 64 and 128 experimental trials.

Displays

All of the tasks reported here were carried out on one of two computers, one with an Intel 386-25 processor, the other with an Intel 486-33 processor. The control programs were prepared using the Microexperiment Laboratory (Schneider, 1995). Stimuli were displayed on identical SVGA monitors. Viewing distance was approximately 46 cm, although head position was not restrained. The letters subtended approximately 1.6° vertically by 1.2° horizontally at that distance.

Procedure

The first tasks were the color- (C) and tone- (T) judgment tasks. The order of these tasks was counterbalanced across participants. Next came the letter-identification tasks, with the manual (M) and voice (V) response blocks counterbalanced. The voice-key calibration sequence was administered just before the oral response block. The dual tasks were blocked by Task 2 response modality; within those blocks, the color and tone versions of Task 1 were administered in ABBA or BAAB order, counterbalanced across participants. This resulted in four orders: CV–TV–TM–CM; CM–TM–TV–CV; TV–CV–CM–TM; and TM–CM–CV–TV.

Results

Analyses of variance (ANOVAs) were carried out on Task 2 and Task 1 RTs, with age group (younger or older) as a between-subjects variable and Task 1 (color and tone discrimination), Task 2 response modality (manual and oral), and SOA (50, 150, 500, and 1,000 ms) as within-subjects variables. All tests were carried out with a .05 significance level. Actual significance levels are reported for information purposes. Sphericity tests were carried out for all analyses; where significant, Greenhouse–Geiser adjusted significance levels are reported.

Task 2 RT

The means and standard deviations for each cell in the design appear in Table 1. There were significant main effects of age group, $F(1, 42) = 13.05, p = .001, MSE = 652{,}878.3$; Task 1, $F(1, 42) = 48.60, p < .001, MSE = 108{,}406.2$; Task 2 response modality, $F(1, 42) = 17.79, p < .001, MSE = 148{,}600.4$; and SOA, $F(3, 126) = 404.98, p < .001, MSE = 14{,}220.3$. There were significant two-way interactions of Task 2 response modality and age group, $F(1, 42) = 12.53, p = .001, MSE = 148{,}600.4$; of SOA and age group, $F(3, 126) = 11.47, p < .001, MSE = 14{,}220.3$; of Task 1 and Task 2 response modality, $F(1, 42) = 14.87, p < .001, MSE = 65{,}515.2$; of Task 1 and SOA, $F(3, 126) = 21.57, p < .001, MSE = 10{,}664.6$; and of Task 2 response modality and SOA, $F(3, 126) = 16.80, p < .001, MSE = 8{,}099.7$. Finally, there were

Table 1
Task 2 Reaction Times (in Milliseconds) as a Function of Task 1, Task 2 Response Modality, Age Group, and SOA

	Task 1–Task 2 SOA							
	50 ms		150 ms		500 ms		1,000 ms	
Task 1/Task 2	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
				Color				
Voice								
Younger	928	254	798	196	678	185	568	165
Older	1,099	260	954	235	761	259	645	212
Manual								
Younger	1,088	346	873	348	681	244	615	240
Older	1,559	419	1,298	514	997	481	895	427
				Tone				
Voice								
Younger	804	233	713	221	552	134	526	137
Older	920	211	830	209	680	202	616	169
Manual								
Younger	761	222	629	201	560	160	518	121
Older	1,159	239	937	192	767	182	695	138

Note. SOA = stimulus-onset asynchrony.

significant three-way interactions of age group, Task 2 response modality, and SOA, $F(3, 126) = 6.23$, $p = .001$, $MSE = 8{,}099.7$; and of Task 1, Task 2 response modality, and SOA, $F(3, 126) = 8.53$, $p < .001$, $MSE = 5{,}856.1$. This complex set of results is best understood by examining the higher order interactions. First, consider those involving age. Task 2 RTs increased as the SOA decreased, more so for older adults than for younger adults. However, as seen in Figure 1, this was true only when both Task 1 and Task 2 required manual responses. Tests of simple interaction effects showed a significant interaction of age group and SOA when both tasks required manual responses, $F(3, 126) = 14.27$, $p < .001$, $MSE = 6{,}878.9$, but no interaction when Task 1 required a manual response but Task 2 required an oral response, $F(3, 126) = 2.02$, $p = .115$, $MSE = 4{,}281.1$. The other three-way interaction involved Task 1, Task 2, and SOA, but did not involve age group. As can be seen in Figure 2, the dual-task interference—that is, the increase in T2 RTs with decreasing SOA—was greater when both tasks required manual responses than when Task 1 required a manual response but Task 2 required an oral response. Color discrimination as Task 1 produced longer RTs than tone discrimination. This difference was greater—and it increased more with reduced SOA—with manual than with oral Task 2 responses. In the same input modality, there was a greater effect of the same output modality.

Regression-Transformed Task 2 RT

One important question is whether the effects on T2 RTs are beyond what would be expected as a result of general slowing. A common approach to compensate for general slowing is a proportional transformation in which each condition mean for an individual is divided by some measure of response latency such as overall mean RT or RT in some baseline condition. Faust, Balota, Spieler, and Ferraro (1999) showed with Monte Carlo simulation that proportional transformations allow an inflated chance of Type I errors in testing for Group × Condition interactions. Moreover, such transformations are inappropriate when the Brinley function (after Brinley, 1965) does not go through the origin. A Brinley plot is a scatter plot of older adult group means as a function of younger adult group means. General slowing can be inferred when the best-fitting function is linear and the slope is greater than 1. A proportional transformation would only be appropriate when the best-fitting line passes through the origin, and this is often not the case. Faust et al. recommended an alternative based on a model that expresses response latency as the product of a rate parameter and the amount of processing required in a task. In practice, the overall means for each condition are regressed on the condition means for each individual, in effect obtaining a Brinley plot for each person. The resulting prediction equation is then applied to the means for the individual, and analyses are carried out on the transformed values. This transformation has the effect of imposing a common information-processing scale on all individuals. This transformation was applied to the T2 RTs. The average value of the regression intercept was 212 ms ($SD = 142$ ms) for the younger adults and 189 ms ($SD = 166$ ms) for the older adults; the difference was not significant, $t(42) = 0.48$, *ns*. The average coefficient for the slope was 0.91 ($SD = 0.34$) for the younger adults and 0.73 ($SD = 0.28$) for the older adults; this difference approached significance, $t(42) = 1.97$, $p = .055$. The important result was that the three-way interaction of age group, Task 2 response modality, and SOA remained significant even after the transformation, $F(3, 126) = 4.91$, $p = .007$, $MSE = 3{,}990.85$. This interaction appears in Figure 3. Thus, the interaction is not accounted for by general slowing of responses in the older adults.

Task 2 Proportion Correct (T2 PC)

There were significant main effects of Task 1, $F(1, 42) = 7.27$, $p = .010$, $MSE = 0.13$, and of SOA, $F(3, 126) = 6.11$, $p = .001$, $MSE = 0.03$. There was also a significant interaction of Task 1 and SOA, $F(3, 126) = 4.60$, $p = .006$, $MSE = 0.02$. No other effects were significant. T2 PC was higher for the tone than for the color task, and was higher for SOAs of 500 and 1,000 ms (*M*s = .93, *SD*s = .01) than for SOAs of 50 or 150 ms (*M*s = .90, *SD*s = .01). The interaction occurred because PC was particularly high with the tone task at the shortest SOA; the proportions correct appear in Table 2.

Task 1 RT

There were significant main effects of age group, $F(1, 42) = 11.98$, $p = .001$, $MSE = 405{,}535.9$; Task 2 response modality, $F(1, 42) = 79.33$, $p < .001$, $MSE = 29{,}001.1$; and SOA, $F(3, 126) = 15.94$, $p < .001$, $MSE = 5{,}146.8$. There were significant two-way interactions of Task 1 and Task 2 response modality, $F(1, 42) = 22.49$, $p < .001$, $MSE = 23{,}688.2$; of Task 1

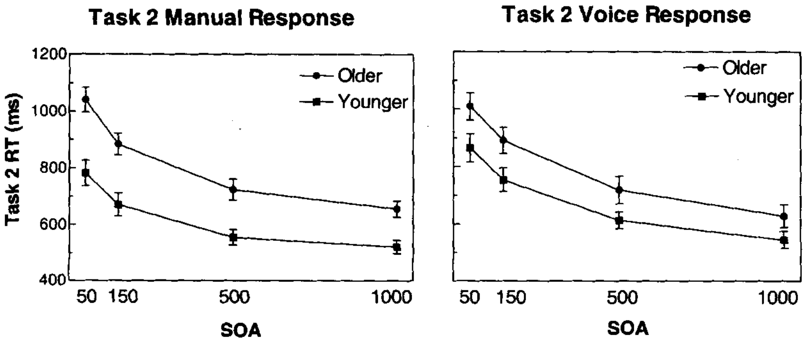

Figure 1. Task 2 reaction times (RT) as a function of age group, Task 2 response modality, and Task 1–Task 2 SOA. Vertical bars represent standard errors. SOA = stimulus-onset asynchrony.

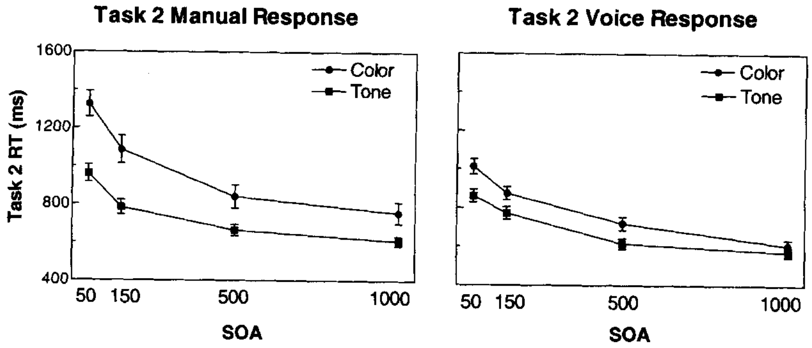

Figure 2. Task 2 reaction times (RT) as a function of Task 1, Task 2 response modality, and Task 1–Task 2 SOA. Vertical bars represent standard errors. SOA = stimulus-onset asynchrony.

and SOA, $F(3, 126) = 8.58$, $p < 0.001$, $MSE = 3{,}403.5$; and of Task 2 response modality and SOA, $F(3, 126) = 7.33$, $p < .001$, $MSE = 3{,}650.0$. Finally, there was a significant three-way interaction of Task 1, Task 2 response modality, and SOA, $F(3, 126) = 4.18$, $p = .009$, $MSE = 2{,}711.0$. There were no significant interactions involving age group; the largest nonsignificant *F* was 0.92. Once again, one can best understand this complex set of results by examining the highest order interaction, the means for which appear in Figure 4. If the second response was to be manual, there was a sharp increase in T1 RT at the shortest SOA, and the increase was greater for the color task than for the tone task. This was evidenced in a significant interaction of Task 1 and SOA when only the manual Task 2 response conditions were considered, $F(3, 126) = 9.88$, $p < .001$. If the second response was to be oral, there was only a modest increase in T1 RT at the shortest SOA, and there was no significant interaction of Task 1 and SOA for oral Task 2 response conditions, $F(3, 126) = 1.58$, $p = .20$. Consistent with this, the increase in T1 RT from 150 ms SOA to 50 ms SOA was significantly greater for manual than for oral Task 2 responses, $F(1, 42) = 32.44$, $p < .001$. The rise was not significantly affected by Task 1, $F(1, 42) = 3.50$, $p = .07$. The effect of Task 2 response modality was not qualified by an interaction with age group, $F(1, 42) = 0.09$, $p = .77$.

Task 1 Proportion Correct (T1 PC)

There were significant main effects of Task 1, $F(1, 42) = 4.48$, $p = .04$, $MSE = 0.02$; Task 2 response modality, $F(1, 42) = 9.44$, $p = .004$, $MSE = 0.02$; and SOA, $F(3, 126) = 10.48$, $p < .001$, $MSE = 0.004$. There was also a significant interaction of Task 1 with Task 2 response modality. The tone task produced higher PCs ($M = .94$, $SD = .01$) than did the color task ($M = .91$, $SD = .02$). A manual response to Task 2 produced higher PCs ($M = .94$, $SD = .01$) than did a voice response ($M = .91$, $SD = .02$). The interaction occurred because the proportion correct was unaffected by Task 1 when a voice response was given in Task 2 ($Ms = .91$, $SDs = .02$); however, with a manual response, the tone task resulted in higher PCs ($M = .97$, $SD = .005$) than did the color task ($M = .92$, $SD = .02$).

Discussion

The results involving age were straightforward. Those concerning the response modality replicated the findings of the earlier study (Hartley & Little, 1999). There was greater interference of Task 1 with Task 2 responding for older adults than for younger adults when both tasks required manual responses. The interference remained greater for older adults when a transformation was applied to adjust for general slowing. However, when the first task required a manual response and the second required an oral response, the interference was identical in the two age groups. This can be interpreted in two ways.

The first interpretation is based on the task-switching model. In this model, increases in Task 2 RT at short SOAs occur because of factors that affect processing before response selection in Task 2 can begin. Presume that at some point the response-mapping rules

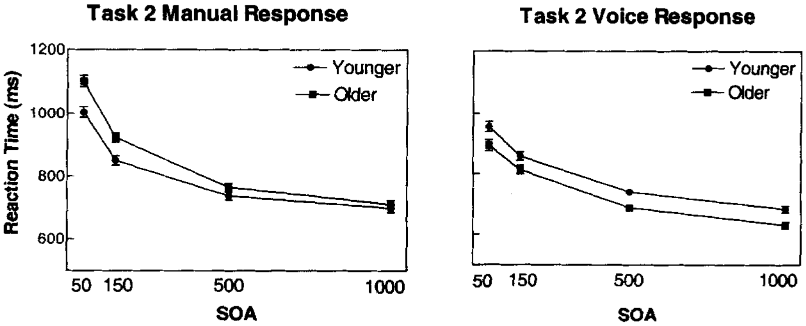

Figure 3. Regression-transformed Task 2 reaction times as a function of age group, Task 2 response modality, and Task 1–Task 2 SOA. Vertical bars represent standard errors. SOA = stimulus-onset asynchrony.

Table 2
Proportion Correct on Task 2

Task	50 ms *M*	50 ms *SD*	150 ms *M*	150 ms *SD*	500 ms *M*	500 ms *SD*	1,000 ms *M*	1,000 ms *SD*
Tone	.94	.08	.91	.06	.94	.06	.94	.06
Color	.86	.14	.88	.14	.92	.08	.91	.10

Note. SOA = stimulus-onset asynchrony.

for each of the tasks must be put into place. If they were both put into place fully before the stimulus for Task 1 arrived, there would be no observable effect whatsoever of putting the mapping rules into place. If the rule for Task 1 can be put into place before the Task 1 stimulus arrives but the Task 2 rule cannot be put into place until the control switches to Task 2, it would have the effect of pushing back the point at which response selection can begin in Task 2. The observed result would have to mean that it takes longer to put in place a Task 2 response rule when that rule involves the same response modality as Task 1, particularly for older adults. Notice that the hand making the response, and therefore the motor cortex programming the response, is different even though both are manual responses. The corresponding motor and premotor cortices are strongly connected via the corpus callosum (Kolb & Whishaw, 1996).

The second interpretation of the result is that it shows a limited capacity for generating similar motor responses, a capacity that is reduced in older adults. The increase in Task 1 RTs at the shortest SOAs is also consistent with a shared capacity—the activation of a second task also involving a manual response draws processing resources away from the first task when they overlap. The results for Task 2 are consistent with a reduced capacity for generation of responses in the same modality in older adults. It must be noted that the increase in Task 1 RTs at short SOAs was not qualified by an interaction with age group. It is important to emphasize that the limited capacity is concerned only with response generation and execution. There was no evidence for an age-related reduction in capacity sharing between the two tasks for response selection. Had the two tasks shared capacity for response selection, RTs in Task 1 would have shown the same sharp increase at short SOAs as did those in Task 2, and older adults would have shown a greater increase than younger adults. I discuss the Task 1 RTs below, but for now I note that there was no evidence whatsoever for an interaction of age group and SOA in Task 1.

The other question that motivated the research was whether there was additional interference if the information for the two tasks was presented in the same modality—that is, whether there is a limited, shared capacity for perceptual processing in a particular modality. The answer appears to be *yes.* Dual-task interference was greater when both tasks involved visual input than when Task 1 used auditory input and Task 2, visual input. With visual input but not with auditory input, perceptual processing of Task 1 must be slowed and the switch to Task 2 pushed back correspondingly when the Task 2 stimulus (the letter) arrives during the processing of the Task 1 stimulus. Because this effect is in no way different for older adults than for younger adults, one can assume that this capacity is not affected by aging. But the story is not as simple as this. There was a significant three-way interaction of Task 1, Task 2, and SOA in Task 2 RTs. Furthermore, it was clear that Task 1 RTs were affected by having the same or different response modalities on Task 2. This means that the sharing of perceptual capacity must have in some way been affecting and been affected by the sharing of capacity for generating motor responses, a completely unanticipated result. A possible explanation for the elevated Task 1 RTs with both stimuli in the same input modality and both tasks requiring manual responses is that some participants were ignoring instructions and grouping their responses in that condition. That is, they would process the information for Task 1 but then withhold the response until Task 2 had been processed, and then output both at the same time. Several

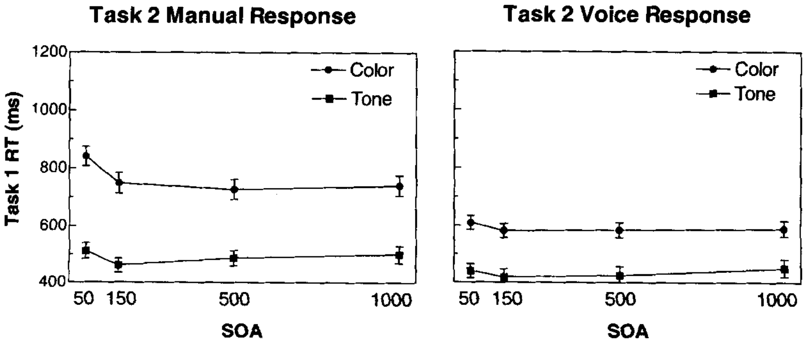

Figure 4. Task 1 reaction times (RT) as a function of Task 1, Task 2 response modality, and Task 1–Task 2 SOA. Vertical bars represent standard errors. SOA = stimulus-onset asynchrony.

investigators have reported grouping of responses (Allen et al., 1998; Hartley & Little, 1999; Pashler, 1984, 1994b). Consistent with grouping, standard errors with a color discrimination for Task 1 and a manual response to Task 2 were, on average, 41% greater than in the other conditions. Another indication of grouping of responses is a failure to respond to Task 1 within the time allotted. Because the response latency is typically much shorter than the time allowed (1,500 ms), these time-out errors are likely to reflect deliberate withholding of the Task 1 response until participants have processed the Task 2 stimulus. ANOVA on time-out errors resulted in a significant interaction of Task 1 and response modality in Task 2. Error rates in the color task were relatively unaffected by the Task 2 response modality (for voice, *M* = .05; for manual, *M* = .04), whereas error rates in the tone task were higher for voice responses (*M* = .08) than for manual responses (*M* = .01); for the interaction, *F*(1, 42) = 11.24, *p* = .002, *MSE* = 0.13. This pattern was exaggerated in the older adults relative to the younger adults, resulting in a significant three-way interaction of Task 1, Task 2 response modality, and age group, *F*(1, 42) = 4.61, *p* = .037, *MSE* = 0.13. Moreover, there was a significant three-way interaction of Task 1, Task 2 response modality, and SOA, *F*(3, 126) = 3.57, *p* = .016, *MSE* = 0.03. The means and standard errors appear in Figure 5. The error rates for voice responses increase at the longest SOAs, as would be expected if the long delay does not allow participants sufficient time to give the withheld Task 1 response after Task 2 is processed. There is no similar increase for manual responses. To the extent that time-out errors are indicative of grouping, grouping was occurring with voice responses, not with manual responses. The increased interference when both stimuli for both tasks are visual and the responses are manual does not appear to be an artifact of response grouping.

Despite the fairly complex results just discussed, the conclusions concerning age differences are simple and straightforward. Combined with earlier findings (Hartley & Little, 1999), the conclusion is that when two simple tasks are superimposed, age differences do not involve perceptual processes or central response-selection processes. They appear to be confined to an age-related limitation in the ability to generate and execute two similar motor programs at the same time.

I argued earlier that the existing evidence strongly favors a task-switching model of dual-task performance over a capacity-sharing or limited-resource model. It is important to note that both are members of the same class of models. A task-switching model is one in which 100% of available resources can be allocated to only one task at a time. Capacity-sharing models simply relax the requirement that all resources be devoted to one task. A remaining question is whether the capacity allocation, whether exclusive or partial, affects all stages of processing.

Pashler (e.g., 1994a, 1994b) has argued that the greatest contributor to dual-task interference is a bottleneck at the stage of response selection. Although perceptual processing of both tasks can proceed in parallel, as can response execution, only one task at a time has access to the resources necessary for response selection. Jolicouer (1999a) pointed out that dual-task procedures such as those used here are fundamentally similar to the procedures used to study what is termed the *attentional blink* (AB, after Raymond, Shapiro, & Arnell, 1992). In such procedures, a stream of stimuli is displayed using rapid serial visual presentation (typically 16 to 22 items, each displayed for 100 ms and with no gap between stimuli). Two targets are embedded in the stream and must be reported after the sequence. Accuracy at reporting the second target is low for targets appearing 100 to 300 ms after the first target, then it gradually recovers until it is at the level of control conditions after about 700 to 800 ms. This closely resembles the interference seen with the present dual-task procedures. Although one might assume that the first target is interfering with the perceptual encoding of the second, Jolicouer (1999c) showed that the interference occurs even for stimuli in different modalities. He argued that the AB and other examples of dual-task interference are best explained by restricted access to central operations occurring after perceptual processing but before initiation of motor commands (Jolicouer, 1999b). He argued that the class of central operations should be broadened beyond response selection to include other operations such as short-term consolidation of stimuli into memory.

Meyer and Kieras (1997a, 1997b) proposed an adaptive executive control architecture for multiple-task performance. They argued that task-switching models incorporating a single, immutable response-selection bottleneck provide a less satisfactory account of multiple-task performance than models incorporating flexible executive control. Consequently, in the architecture proposed by Meyer and Kieras, bottlenecks may be placed at a number of points in the processing sequence. Whether and where the bottlenecks are placed are under strategic control. De Jong (1993) reported results consistent with the presence of two bottlenecks: one at response

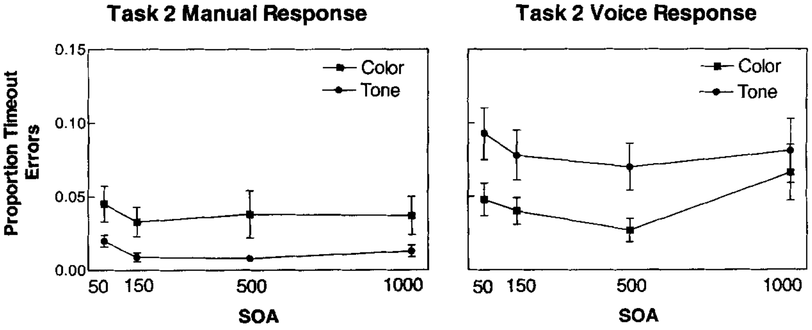

Figure 5. Proportion of timeout errors on Task 1 as a function of Task 1, Task 2 response modality, and Task 1–Task 2 SOA. Vertical bars represent standard errors. SOA = stimulus-onset asynchrony.

selection, the other at response initiation. As Pashler (1998) noted, the presence of an effector-specific bottleneck in response execution is in no way incompatible with the well-established modality-independent bottleneck in response selection. De Jong's finding is mute on whether the effector bottleneck is under strategic control. Consonant with Meyer and Kieras's argument that the response-selection bottleneck is the result of strategic choices, Schumacher et al. (1999) reported dual-task procedures that failed to find evidence of a response-selection bottleneck. Nothing in the present results contradicts the possibility that access to central operations other than response selection may be limited, nor do these results provide counterevidence to the flexible executive control model. Of course, neither do the present results provide any specific support. Whether the architecture is fixed or under strategic control, it appears that in these tasks the functional architecture is the same for the younger and older adults.

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