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Age-Related Differences and Similarities in Dual-Task Interference

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Differences between younger adults (mean age, 20.7 years) and older adults (mean age, 72.7 years) in dual-task performance were examined in 7 experiments in which the overlap between 2 simple tasks was systematically varied. The results were better fit by a task-switching model in which age was assumed to produce generalized slowing than by a shared-capacity model in which age was assumed to reduce processing resources. The functional architecture of task processing appears the same in younger and older adults. There was no evidence for a specific impairment in the ability of older adults to manage simultaneous tasks. There was evidence for both input and output interference, which may be greater in older adults.

Advancing age is commonly accompanied by a decline in performance on a wide variety of cognitive tasks, both in the laboratory and in everyday life. Parsimonious accounts of these pervasive changes ascribe them to changes in some basic attribute of cognitive operations, something involved in virtually all higher level functioning (Salthouse, 1988a). The attribute has been identified variously as the speed of processing, the capacity of working memory, or the capacity of attention (see, e.g., Salthouse, 1988b). The 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 appear 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 than in younger adults.

The empirical evidence supports the prediction that secondary-task performance will be poorer in older 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, 1991, described in detail by Hartley, 1992). This would appear to support the claim of a reduced resource in older adults, but many of the experiments are vulnerable to serious methodological criticisms (Guttentag, 1989; Hartley, 1992; Salthouse, 1991). For example, older and younger groups are seldom equated on single-task performance, and, as a result, the apparent dual-task deficit may be no more than a reflection of underlying differences in performance on the tasks done alone. Nonetheless, most studies that have avoided the methodological criticisms still have found greater dual-task costs in older than in younger adults (Crossley & Hiscock, 1992; Korteling, 1991; Salthouse, Rogan, & Prill, 1984; but not Somberg & Salthouse, 1982).

Attributing age differences in dual-task costs, even in well-controlled studies, to a reduction in resource is premature. In some studies, both tasks are complex and require multiple operations: For example, Salthouse et al. (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 is 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. (1984) and Crossley and Hiscock (1992) 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.

An alternative approach was used in the experiments reported here. Two simple, well-learned tasks were carried out on each trial. The relative onsets of the stimuli for the two tasks were controlled so that the time course of interference could be explored systematically. Specifically, each trial began with the presentation of a white *X*. After 500 ms the color was changed, in most of the experiments to red or green. In Task 1, participants gave 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

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ms—the *X* was replaced by an *A* or *B* (the color remained the same). In Task 2, participants gave 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, the tasks are both simple, in comparison, for example, to holding two lists that are close to maximum span in memory. 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, the response to Task 1 will have already been executed before the stimulus for Task 2 is presented. This is a valuable extension to the standard single-task control condition. At long SOAs, the second task is done in the dual-task context, although the processing of Task 1 should be fully completed. Finally, the reduced-resource theory makes predictions about performance on this task that are distinctly different from alternative theories.

Theories of Dual-Task Performance

Capacity Sharing

Resource-reduction theories of age differences belong to the general class of theories that assume there is a fixed capacity and that the capacity must be shared among all active tasks. Some theorists have argued for a single, common resource (Kahneman, 1973), whereas others have argued for multiple resources (Navon & Gopher, 1979; Wickens, 1984). For simplicity, we begin with a model that assumes a single resource, modifying the model if the evidence requires it. The allocation of resources as a function of time in the present experiments is shown in Figure 1 (Panel A). At the outset, all of the resources are committed to Task 1. When the second stimulus appears, some of the resources are redirected to Task 2; all the resources are shifted to Task 2 once the response for Task 1 has been generated. Increased age is assumed to reduce the available capacity as shown in Figure 1 (Panel B). Figure 2 shows the predicted reaction time (RT) to Task 2 as a function of age group and the SOA between the stimuli for the two tasks. Dual-task interference should be greatest at the shortest SOAs and diminish with increasing separation between the tasks. There should be an overadditive interac-

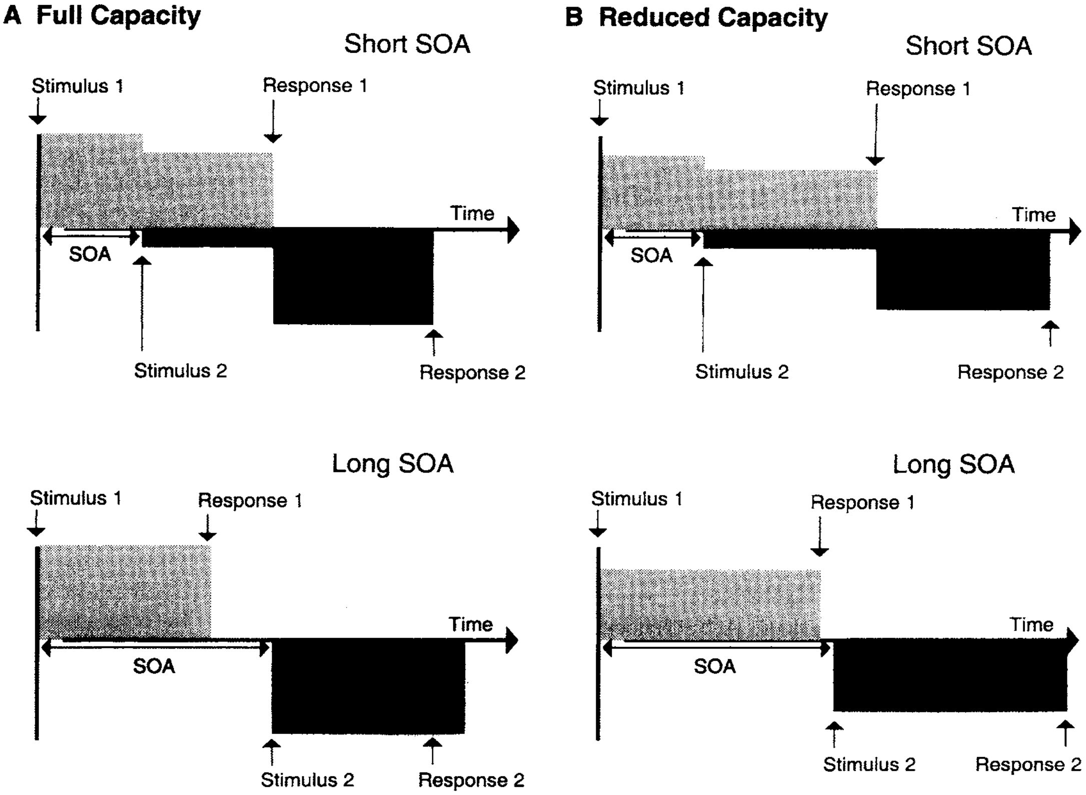

Figure 1. The shared-capacity model of dual-task performance. (A) The time course of events on a trial. (B) The time course of events with resources reduced relative to Panel A. The upper panels show a trial with stimulus onset asynchrony (SOA); the lower panels show a trial with long SOA.

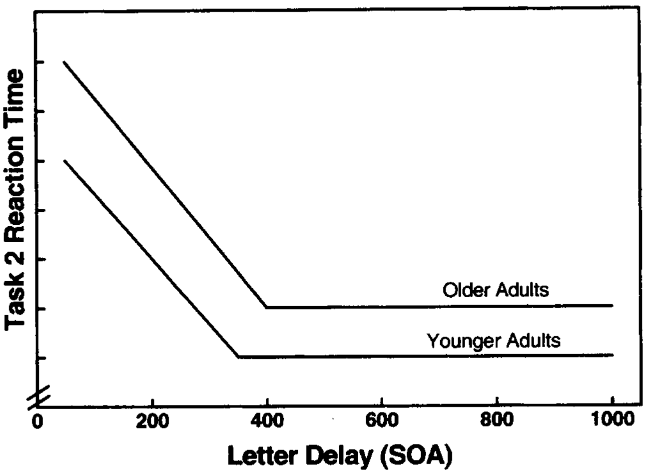

Figure 2. Predicted Task 2 performance as a function of letter delay for older and younger adults for both the capacity-sharing and task-switching models. SOA = stimulus onset asynchrony.

tion of age and SOA with age differences smallest at the longest SOA and greatest at the shortest SOA. (Although it runs counter to the convention of moving from left to right along the abcissa in describing results, it is more natural here to move from right to left, from long SOAs to short SOAs.) Similarly, reaction times in Task 1 should decrease with increasing SOA. At short SOAs, when the tasks overlap, capacity must be shared between them; at long SOAs, full capacity can be devoted to each task in turn. Reduced capacity will exaggerate the effects of task overlap, resulting in an overadditive interaction of age and SOA. Overadditive interactions are a hallmark of capacity sharing: Factors that reduce available capacity (such as age) or that demand more of it (such as more complex tasks) should evidence greater effects of the factor at short SOAs than at long SOAs (McCann & Johnston, 1992; McLeod, 1977).

Task Switching

An alternative that has received considerable empirical support is the 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) shown in Figure 3 (Panel A). This model assumes that there is a single response-selection mechanism. Task 2 cannot have access to this mechanism and, so, cannot proceed with response selection until the mechanism is freed by Task 1. A bottleneck is created because only one task at a time can have access to the response-selection mechanism. In this model, early perceptual processing in the two tasks can be carried out in parallel. Similarly, response initiation and execution in Task 1 can be carried out in parallel with processing in Task 2. These predictions are explored in experiments reported here. De Jong (1993) and Meyer et al. (1995) have proposed models in which there are (or optionally may be) other bottlenecks in addition to that created by the response-selection mechanism, but, for simplicity, we begin with a model that assumes a single bottleneck and modify it as the evidence warrants. The most straightforward extension of this model to account for age differences is to assume that there is generalized slowing in older adults but that the system is structurally identical to that in younger adults. This is shown in Figure 3 (Panel B). The age differences predicted by the task-switching model are the same as those predicted by the capacity-sharing model, shown in Figure 2. The task-switching model predicts an increase in dual-task interference with decreasing SOA, just as does the capacity-sharing model. Moreover, because all stages are proportionately lengthened in older adults, the effects of age should also be overadditive with those of SOA. At short SOAs when the tasks overlap, slowing in Task 1 will add to the slowing in Task 2, whereas, at long SOAs, Task 1 will have cleared, and only the slowing in Task 2 will be present. In clear contrast to the capacity-sharing model, the task-switching model predicts that RTs in Task 1 should be unaffected by SOA. Because Task 1 gains first access to the response-selection mechanism, only Task 2 will be affected by having to wait. Older adults will be slower, but they, too, should show no effect of SOA on Task 1 RTs.

Relations Between the Models

Despite their apparent differences, the capacity-sharing and task-switching models are fundamentally related. The capacity-sharing model assumes that all stages of processing are capacity limited. There may be a single pool of resources or there may be separate pools subserving different stages. At each stage, capacity may be allocated between concurrent tasks. The task-switching model assumes that only the response-selection stage is capacity limited and, further, that the allocation of resources to response selection in a task is all or none. Perceptual-processing and response-execution stages are postulated not to be capacity limited.

Experiment 1

The first experiment compared younger and older adults on the basic dual-task procedure described in the introduction to determine whether the results were more consistent with the capacity-sharing or the task-switching model.

Method

Participants

Descriptive statistics for the participants in all of the experiments reported here are given in Table 1. The older adults were volunteers from the local community who transported themselves to the testing site; they received a payment of $10 per hour for their participation. The younger adults were college students; most participated for optional extra credit in psychology courses, although some were paid at the same rate as the older adults.

Design and Procedure

Color-alone task. Participants first completed 125 trials on the color task alone. Each trial began with presentation of the letter *X* in

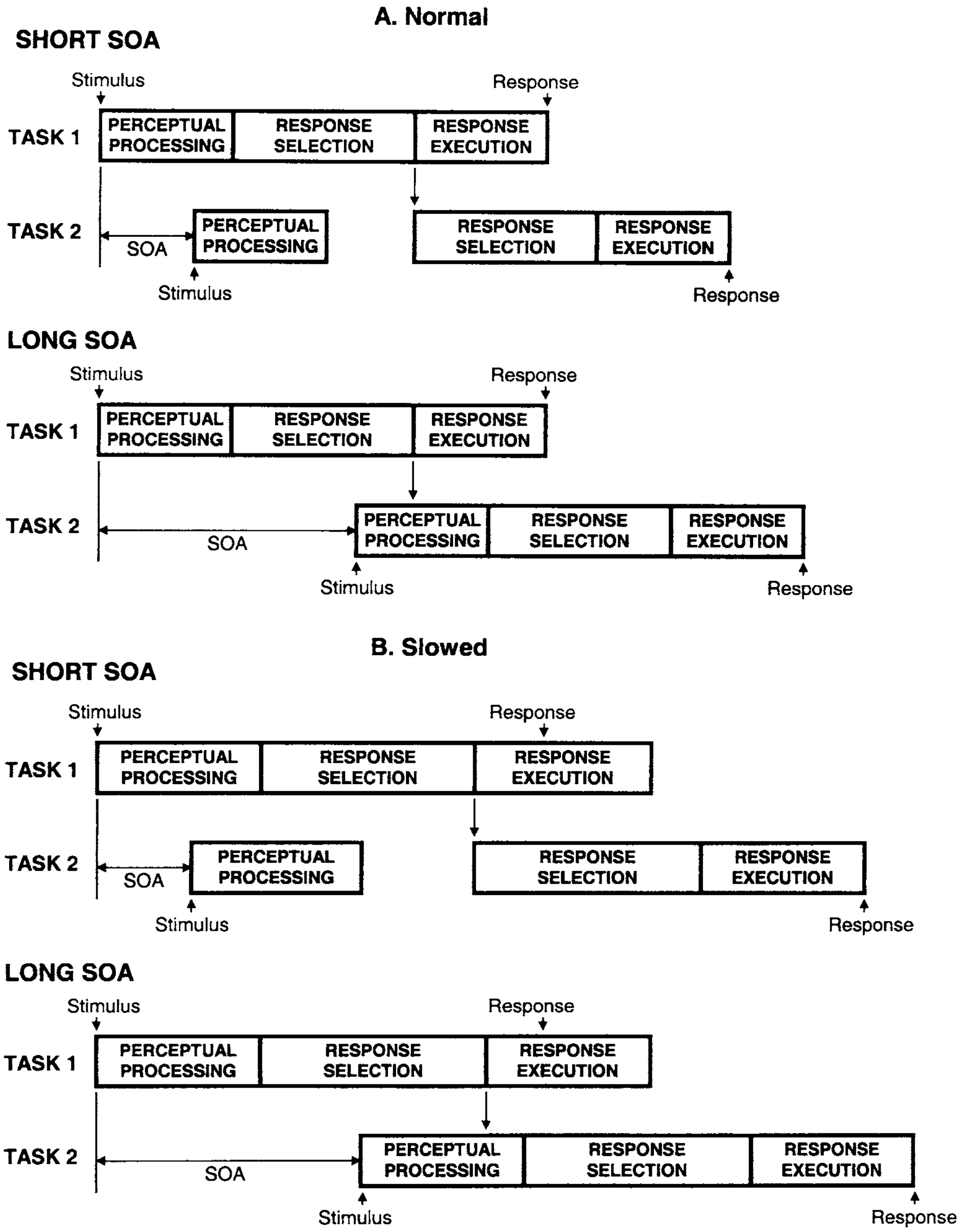

Figure 3. The task-switching model of dual-task performance. (A) The time course of events on a trial. (B) The time course of events incorporating age-related slowing. The upper panels show a trial with stimulus onset asynchrony (SOA); the lower panels show a trial with long SOA.

white centered on the display. After 500 ms, the color was changed to green or red. The participant was instructed to identify the color as quickly as possible by pressing the *z* key with the middle finger of the left hand for red or the *x* key with the index finger of the left hand for green. The fingers rested on the keys. Labels (RED and GREEN) 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 and data from those trials were not analyzed. Participants were allowed to rest after the practice trials and after 50 experimental trials.

Letter-alone task. Participants next completed 125 trials on the letter task alone. Each trial began with presentation of the letter *X* in white centered on the display. After 500 ms, the *X* was replaced by an *A* or *B* 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 by pressing the period key with the index finger of the right hand for A or the slash key with the middle finger of the right hand for B. Labels (A and B) were placed just above the keys. 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.

Table 1
Participant Characteristics

Participants	Age		Women	Men	Education		Health		Acuity	
	M	Range			*M*	*SD*	*M*	*SD*	*M*	*SD*
Experiment 1										
Younger	21.25	18–39	44	16	13.78	1.49	8.10	1.35	20.91	3.75
Older	72.01	60–85	37	23	16.00	3.15	8.45	1.35	26.00	6.11
Experiment 2										
Younger	19.62	18–23	16	4	13.14	1.11	8.33	1.06	20.24	1.09
Older	74.65	62–85	13	7	15.05	3.41	8.00	1.17	26.25	6.66
Experiment 3										
Younger	20.80	18–38	17	3	13.70	1.59	7.25	1.83	23.25	8.16
Older	72.00	62–81	14	6	16.40	2.89	8.65	1.04	27.25	8.50
Experiment 4										
Younger	20.00	18–38	16	4	13.55	0.94	7.85	1.35	21.75	5.20
Older	69.70	60–79	13	7	16.95	2.87	8.60	1.67	25.50	5.10
Experiment 5										
Younger	19.15	18–21	14	6	13.50	0.69	7.15	1.63	24.12	11.21
Older	73.33	63–86	13	7	16.45	2.86	8.16	1.54	28.57	9.37
Experiment 6										
Younger	19.55	19–22	15	5	13.15	0.36	8.78	3.04	23.68	9.58
Older	75.45	64–88	11	9	15.78	2.86	8.93	0.85	28.42	6.50
Experiment 7										
Younger	24.20	19–39	14	6	14.70	2.13	8.10	1.59	20.75	3.73
Older	71.70	62–85	12	8	16.00	3.16	8.75	1.16	26.25	6.46

Note. Health is a subjective rating on a 1–10 scale. Acuity is Snellen Visual Acuity at 20 feet.

Participants were allowed to rest after the practice trials and after 50 experimental trials.

Dual task. The dual task was completed last. Each trial began with presentation of the letter *X* in white centered on the display. After 500 ms, the color was changed to green or red. The participant was instructed to respond as in the color-alone task. At an SOA of 50, 150, 500, or 1,000 ms after the color changed, the *X* was replaced by an *A* or *B* (the color remained the same). The stimulus was changed back to a white *X* 200 ms after the *A* or *B* had appeared. The participant was instructed to respond to the letter as in letter-alone task. The time allowed for a response to the color was 1,500 ms; for the letter, the time was 5,000 ms. The instructions emphasized responding as quickly as possible to each task. Errors were signaled by tones, a high tone for color errors and a low tone for letter errors. 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.

In this experiment and in the subsequent experiments, after informed consent was obtained and before the experimental tasks were performed, participants were asked their year of birth and highest level of education achieved, and they were asked to provide a subjective rating of health. The health rating was a subjective self-report of the participant's current state of health using a 10-point scale on which 10 was *excellent.* After the experimental tasks were completed, visual acuity was measured using the Snellen chart, viewed binocularly at a distance of 20 feet, using corrective lenses if those were normally worn. Participants were also tested for color blindness; none was rejected for this reason.

Displays

All of the experiments reported here were controlled by two computers, one with an Intel 386-25 processor, the other with an Intel 486-33. The control programs were prepared using the Micro Experiment Laboratory (MEL, Schneider, 1990). Stimuli were displayed on identical SVGA monitors. Viewing distance was approximately 46 cm, although head position was not restrained. The letters *X* and *A* were 10 mm in width × 12 mm in height or about 1.25° × 1.49°; the letter *B* was 8 mm × 12 mm or about 1.00° × 1.49°.

Results

For all analyses in this and the subsequent experiments, alpha was set at 0.05. Tests for sphericity were carried out in each analysis. Greenhouse-Geisser corrected significance levels are reported for any effect for which the sphericity test was significant. For all analyses reported here, RTs less than 200 ms or longer than the longest time allowed for a response were treated as errors. Those trials were excluded from analyses of RTs.

Color-Alone Task

An analysis of variance (ANOVA) on correct RTs in the color-alone task showed that younger adults responded more quickly ($M = 455$ ms) than older adults ($M = 520$ ms), $F(1, 118) = 21.90$, $p < .001$, $MSE = 5{,}375.27$. There was no significant difference in the proportion of correct responses between younger adults ($M = 0.97$) and older adults ($M = 0.96$), $F(1, 118) = 0.04$, *ns*, $MSE = 0.01$.

Letter-Alone Task

An ANOVA on correct RTs in the letter-alone task showed that younger adults responded more quickly ($M = 425$ ms) than older adults ($M = 472$ ms), $F(1, 118) = 12.17$, $p <$

.001, $MSE = 4{,}280.35$. There was a significant difference in the proportion of correct responses for younger adults ($M = 0.97$) and for older adults ($M = 0.96$), $F(1, 118) = 4.79$, $p = .03$, $MSE = 0.001$.

Dual Task

Task 2. Mean RTs in the second (letter) task (RT2s) are shown in Figure 4. An ANOVA was carried out on the RT2s with age group as a between-subjects variable and SOA as a within-subjects variable. There were significant main effects of age group and SOA as well as a significant interaction of those two factors: For age group, $F(1, 118) = 42.72$, $p < .001$, $MSE = 134{,}941.26$; for SOA, $F(3, 354) = 823.75$, $p < .001$, $MSE = 8{,}121.35$; for the interaction, $F(3, 354) = 11.34$, $p < .001$, $MSE = 8{,}121.35$. As can be seen from Figure 4, RT2s increased as the SOA decreased, that is, as the overlap between the two tasks increased. The interaction of age group and SOA was overadditive: Older adults were 155 ms slower on average at an SOA of 1,000 ms, and the difference increased to 274 ms at an SOA of 50 ms. An ANOVA on the proportion of correct responses (ACC2) showed only a significant main effect of age group, $F(1, 118) = 9.91$, $p = .002$, $MSE = 0.62$. ACC2 was higher for younger adults ($M = 0.91$) than for older adults ($M = 0.84$). Neither the effect of SOA nor the interaction of age group and SOA were significant: For SOA, $F(3, 354) = 2.04$, $p = .16$, $MSE = .01$; for the interaction, $F(1, 118) = 2.16$, $p = .14$, $MSE = 0.01$.

Task 1. Mean RTs in the first (color) task (RT1s) are shown in Figure 5. An ANOVA was carried out on the RT1s with age group as a between-subjects variable and SOA as a within-subjects variable. There were significant effects of age group and SOA; the interaction was not significant: For age group, $F(1, 118) = 6.01$, $p = .02$, $MSE = 118{,}890.27$; for SOA, $F(3, 354) = 24.14$, $p < .001$, $MSE = 6{,}094.07$; for the interaction, $F(3, 354) = 1.07$, *ns*, $MSE = 6{,}094.07$. RTs were longer in older adults; in both age groups, RTs dropped with increasing separation between the tasks but increased slightly at the longest SOA, 1,000 ms. Analysis of the proportion of correct responses (ACC1) showed significant effects of age group and of the interaction of age group and SOA: For the main effect of age group, $F(1, 118) = 10.89$, $p < .001$, $MSE = 0.07$; for the interaction, $F(3, 354) = 7.15$, $p = .009$, $MSE = 0.01$. The main effect of SOA was not significant, $F(3, 354) = 3.30$, $p = .07$, $MSE = 0.01$ (although by a conventional test it would have been $p = .02$). For 50-, 150-, 500-, and 1,000-ms SOA, the ACC1s were 0.95, 0.96, 0.96, respectively, and 0.90 for younger adults and 0.82, 0.86, 0.88, and 0.88 for older adults. Both age groups were somewhat less accurate on trials with the shortest SOA, although the effect was greater in the older adults. In contrast, younger adults showed a dropoff in performance at the longest SOA, whereas older adults did not.

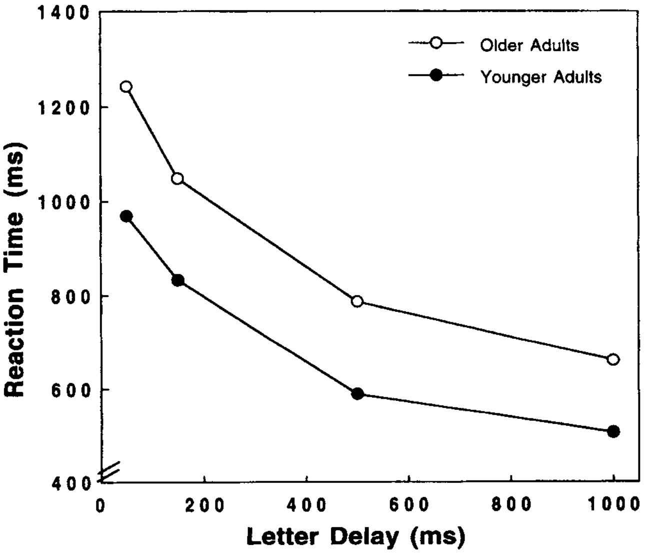

Figure 4. Mean Task 2 reaction time as a function of letter delay for younger and older adults in Experiment 1.

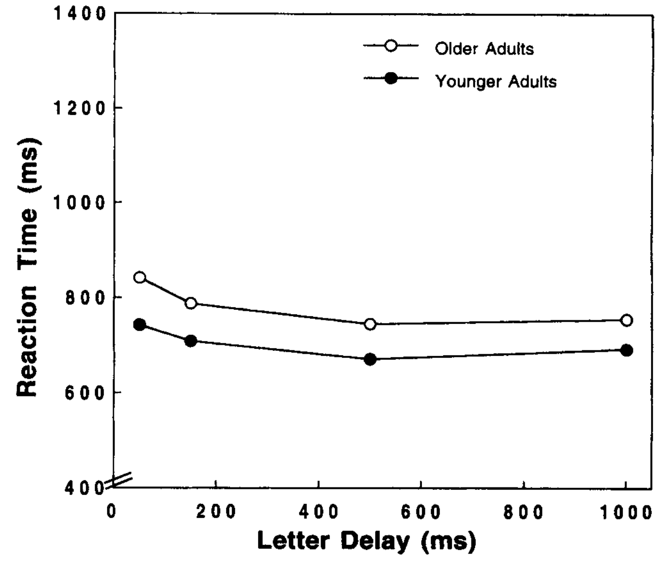

Figure 5. Mean Task 1 reaction time as a function of letter delay for younger and older adults in Experiment 1.

Dependencies between Task 2 and Task 1. An additional analysis was carried out to determine whether RT1 affected RT2, modeled on the analysis used by Pashler (e.g., 1989). Trials were sorted on the basis of RT1 into those in the fastest third or tertile, the middle tertile, and the slowest tertile. The relation between SOA and RT2 was examined as a function of the tertile of RT1. For the analysis, age group was a between-subjects variable, and SOA and tertile were within-subjects variables. The new effects are those involving the tertile variable; the significant effects were the main effect of tertile, $F(2, 236) = 558.02$, $p < .001$, $MSE = 24{,}278.82$, and the interaction of SOA and tertile, $F(6, 708) = 97.20$, $p < .001$, $MSE = 9{,}668.59$. The interaction of age group with tertile was not significant, $F(2, 236) = 1.20$, *ns*, $MSE = 24{,}278.82$, nor was the interaction of age group, tertile, and SOA, $F(6, 708) = 1.54$, *ns*, $MSE = 9{,}668.59$.

The means are shown in Figure 6. Generally, trials with longer RT1s resulted in longer RT2s and, conversely, shorter RT1s resulted in shorter RT2s. The dependency was greatest at the shortest SOAs.

Discussion

Dual-Task Costs

There was clear evidence that performing each of the tasks in the dual-task context was more difficult than performing each of them alone. This can be seen by comparing the RT for each of the tasks alone with the corresponding RT at the longest SOA when they were combined. At a 1,000-ms SOA, the response to Task 1 very likely will have been given before the stimulus for Task 2 appears, so they are in effect sequential rather than simultaneous tasks. For Task 1, the color task, older adults were 236 ms slower in the dual task than in the same task done alone (756 ms compared with 520 ms), and younger adults were 238 ms slower (693 ms compared with 455 ms). For Task 2, the letter task, older adults were 189 ms slower (661 ms compared with 472 ms), whereas younger adults were 81 ms slower (506 ms compared with 425 ms). Thus, there were dual-task costs even when the tasks were not superimposed. These costs include preparing and maintaining two sets of stimulus-response mappings.

Task 2

Both the capacity-sharing model and the task-switching model predicted that RTs would increase as the SOA was decreased. Moreover, both models predicted that the increase would be greater for older adults, resulting in an overadditive interaction of age group and SOA. This interaction was found.

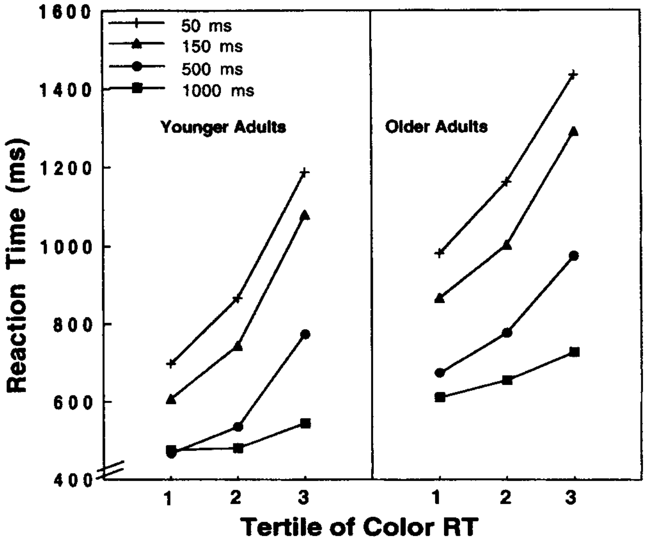

Figure 6. Mean Task 2 reaction time (RT) as a function of letter delay and fastest, middle, or slowest third (tertile) of Task 1 RTs for younger and older adults in Experiment 1.

Task 1

RT1s also increased with decreasing SOA. This result is consistent with the capacity-sharing model but not the task-switching model. If capacity is shared between Task 1 and Task 2 when they overlap, RT1 should be increasingly lengthened as the overlap is increased. By contrast, in the task-switching model, RT1 should be unaffected by the SOA. Because Task 1 has first access to the response-selection mechanism, it should be unaffected by the onset of Task 2. The present result, however, disagrees with a number of studies that have found no effect of SOA on RT1 or only a modest increase at the shortest SOAs (De Jong, 1993; Fagot & Pashler, 1992; McCann & Johnston, 1992; Osman & Moore, 1993; Pashler, 1991, 1993, 1994b; Pashler, Carrier, & Hoffman, 1993; Pashler & Johnston, 1989; Pashler & O'Brien, 1993). Nevertheless, the support for the capacity-sharing model is not unequivocal, as that model predicts an interaction between age group and SOA in RT1 that was not found.

An alternative explanation for the relationship between RT1 and SOA is that participants (or at least some participants on some trials) were violating the instructions and grouping their responses, that is, withholding the response to Task 1 until processing was complete or nearly complete in Task 2 and then making both responses in quick succession (cf. Pashler, 1984, 1994c). The simplest model of grouping is that the Task 1 response is withheld until processing of Task 2 is complete and the response is ready. This model predicts that RT1 will be a monotonic function of the SOA plus RT2. (The simple sum of those two times would overestimate RT1, as the initiation of the second response must be withheld until the first response is launched.) This model predicts that RT1 will drop slightly from the 50-ms SOA to the 150-ms SOA and then rise sharply for SOAs of 500 and 1,000 ms. This model does not fit the data. Assume, however, that grouping is most likely to occur when the stimuli overlap. If grouping was most likely at 50-ms SOA, somewhat less likely at 150-ms SOA, and relatively unlikely at longer SOAs, grouping could account for the increase in RT1 at shorter SOAs. There should be empirical indicators if grouping is occurring. First, withholding the Task 1 response should lead either to failures to respond within the allotted 1,500 ms (timeout errors) or to relatively long RT1s. At short SOAs, it is more likely the response can be withheld and still completed before the deadline; at long SOAs, it is either unlikely or impossible. In the simple model, then, as the SOA is lengthened, response grouping should lead to a monotonic increase in the frequency of timeout errors and, concomitantly, to a monotonic increase in the frequency of long RT1s. Figure 7 shows the mean proportion of timeout errors (Panel A) and of long RTs (arbitrarily defined as 1,000 ms or longer, Panel B). An ANOVA on the proportion of timeout errors produced significant effects of age group, $F(1, 118) = 10.10$, $p = .002$, $MSE = 0.08$, and of the interaction of age group and SOA, $F(3, 354) = 6.88$, $p <$

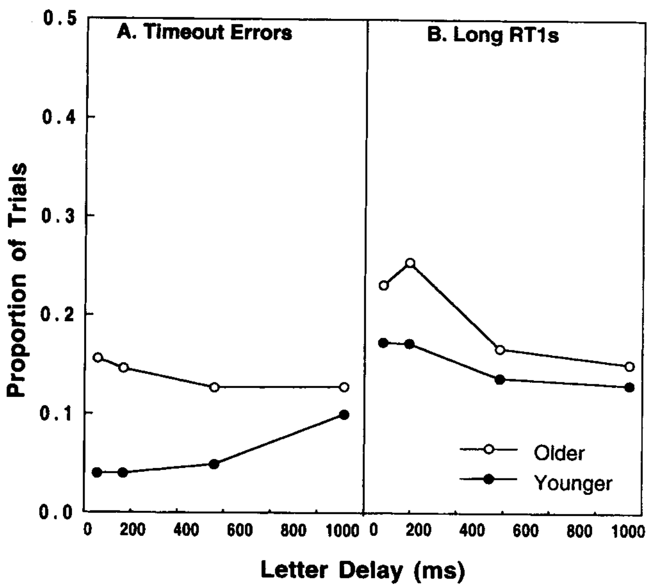

Figure 7. (A) Proportion of timeout errors (failures to respond within 1,500 ms) as a function of letter delay and age group in Experiment 1. (B) Proportion of long Task 1 reaction times (RT1s) (between 1,000 ms and 1,500 ms) in Experiment 1.

.001, *MSE* = 0.01. Analysis of the long RTs produced significant main effects of age group, $F(1, 118) = 3.92, p = .050$, $MSE = .07$, and of SOA, $F(3, 354) = 13.75, p < .001$, $MSE = 0.01$; the interaction was not significant, $F(3, 354) = 1.72$, $p = .175$, $MSE = 0.01$. Older adults appeared more likely to withhold responses than younger adults and in a pattern suggestive of withholding responses at shorter SOAs: Both timeout errors and long RTs were frequent, and they were more frequent at the two shortest SOAs than at the two longest SOAs. Younger adults showed a pattern suggestive of withholding the response for a certain period of time, independent of SOA: Long RTs were more frequent at short SOAs, whereas timeout errors were more frequent at long SOAs. Withholding the response would, of course, have the greatest effect on RT1. But, if the Task 1 response is not emitted until after Task 2 processing is complete, and only then is the Task 2 response given, that would also lengthen the RT2. Nevertheless, a pattern of withholding responses that produced an interaction of age group and SOA in RT2 should also do so in RT1. The presence of an interaction of age group and SOA in RT2 but absence of that interaction in RT1 is problematic for the response-withholding hypothesis.

Dependencies Between Task 1 and Task 2

There was a direct relationship between RT2 and RT1: Relatively longer RT1s were accompanied by longer RT2s, particularly at short SOAs. As Pashler (e.g., 1994a) has noted, the task-switching model predicts this result. At short SOAs, on a trial with a relatively long RT1, the second task must wait longer for access to the response-selection mechanism. At long SOAs, this will not be true because the mechanism will have been freed long before it is needed for Task 2. Capacity-sharing models cannot obviously account for this result (Fagot & Pashler, 1992). Probably the most straightforward extension of the capacity-sharing model is to assume that capacity is fixed and that a relatively short RT1 occurs when Task 1 is assigned more of the available capacity, whereas a relatively long RT1 occurs when Task 1 is assigned less. Curiously, this model predicts that RT2 will be completely unaffected by variation in RT1. When more capacity is assigned to Task 1, the full capacity becomes free earlier for transfer to Task 2; when less capacity is assigned to Task 1, Task 2 has the benefit of greater resources prior to Task 1 completion. There is a perfect trade-off between the two. An alternative capacity-sharing model provides a better account of the results. Suppose that capacity is not fixed but varies from trial to trial (as might happen if irrelevant thoughts or environmental events intruded). Suppose further that the proportion of resources assigned to Task 1 and to Task 2 when they overlapped was the same on every trial. In this model, a trial with relatively high capacity would produce short RT1s and short RT2s, whereas a trial with relatively low capacity would produce long RT1s and RT2s. This would result in the direct relationship between RT1 and RT2 that was observed. The difficulty is that this dependency should be observed not only at short SOAs but also at long SOAs. If the capacity is relatively high, then both Task 1 and Task 2 should be executed quickly even when there is no sharing of the capacity. Similarly, low capacity would result in slow responses in both tasks. Thus, this model is consistent with the dependencies at short SOAs that were observed but not the relative independence of the two tasks at long SOAs.

Assessment of the Models

Both models correctly predicted the increase in RT2 at shorter SOAs. They also correctly predicted an interaction of age group and SOA, with older adults differentially slowed at the shortest SOAs. The increase in RT1 at shorter SOAs, however, is consistent with the capacity-sharing model but not the task-switching model. Reduced capacity in older adults should also have produced an interaction of age group and SOA in RT1, just as it did in RT2, but this interaction was not significant. The age differences in RT1s did increase from 64 ms at 1,000-ms SOA to 100 ms at 50-ms SOA. It is possible that the design simply lacked sufficient power to detect the weak interaction as significant. It is not the case that the first task, color discrimination, was simply faster than the second task, letter discrimination, so that an interaction that was proportionally the same would be absolutely smaller for the color task: Mean RTs in the letter-alone task were faster than those in the color-alone task (for younger adults, 425 ms compared with 455 ms; for the older adults, 472 ms compared with 520 ms) as were mean RTs at the longest SOA (for younger adults, 506 ms compared with 693 ms; for older adults, 661 ms compared with 756 ms). The clearest failure of the capacity-sharing model was the inability to account for the dependency of RT2 on RT1: the increase in RT2 for progressively slower

RT1s at short SOAs and a relative independence of the two at the longest SOAs.

The task-switching model cannot account for the increase in RT1 at shorter SOAs. In the task-switching model, RT1 should be independent of the overlap between the two tasks because Task 1 is given first access to the response-selection mechanism. As noted, the increase in RT1 at short SOAs is incompatible with a substantial number of previous studies that have found RT1 to be independent of SOA. It is possible to rescue the task-switching model by assuming that at least some participants on some trials group responses, withholding the response to Task 1 until processing on Task 2 is nearly complete. If it is further assumed that older adults are more likely to withhold their responses than younger adults and that the likelihood they will do so is greatest at the shortest SOAs, the resulting hybrid model may account for the findings for both RT2 and RT1. The data for timeout errors and long Task 1 RTs support these assumptions. Notice that a grouping model that does not incorporate task-switching is insufficient. Grouping alone would not cause RT2 to be longer at shorter SOAs. Unlike the shared-capacity model, the task-switching model accounts straightforwardly for the pattern of dependencies between RT2 and RT1.

A hybrid model that incorporates both task switching and response grouping appears to give the best account of the data. Pashler (1984) has proposed a similar model to account for some dual-task results. It is, however, premature to reach any theoretical conclusions on the basis of the first experiment. Not only is the hybrid model ad hoc, it is also unparsimonious. A simple grouping model would predict that RT1 would increase with increasing SOA, with longer SOAs requiring that the color response be held for a longer time. It was necessary to assume that the probability of grouping was greater in older adults and that it decreased with increasing SOA. Moreover, it was necessary to assume that the likelihood of grouping at short SOAs was greater in older adults. By tuning the assumed likelihood of grouping in different groups and conditions, it would have been possible to account for virtually any observed relationship between RT1 and SOA.

Experiment 2

The task-switching model predicts that dual-task interference can be eliminated simply by removing competition for the response-selection mechanism, the source of the processing bottleneck (Pashler, 1989; Pashler & Johnston, 1989). Competition for the response-selection mechanism can be removed by eliminating the requirement for a speeded response to Task 2. In practice, participants are instructed to respond to Task 1 as quickly as possible, but they are instructed to take their time with Task 2; often responses to Task 2 are not permitted until a second or more after the stimulus to discourage rapid responding. According to the model, at short SOAs the perceptual processing of the stimuli for Task 1 and Task 2 will take place at the same time, but, because these processes can proceed in parallel, the tasks will not interfere.

The capacity-sharing model makes very different predictions. Even if the response to Task 2 can be postponed, at short SOAs the stimuli will still overlap, and processing resources must be shared between the two tasks. Thus, both Task 1 and Task 2 should continue to show impaired performance at short SOAs.

The second experiment was very similar to the first except that participants were instructed to take their time with Task 2 and not to try to speed their response. For this reason, RT could no longer be the dependent variable. Instead, the duration for which the letter was displayed was reduced and accuracy was measured. With accuracy as the dependent variable, the capacity-sharing model predicts that accuracy should decrease with decreasing SOA in Task 2. RT remains the dependent variable in Task 1, so the capacity-sharing theory still predicts that RT will increase as SOA decreases. The task-switching model predicts that accuracy will be independent of SOA.

Method

Participants

The participants in Experiment 2 were 20 younger adults and 20 older adults from the same populations as Experiment 1. Their characteristics are given in Table 1.

Procedure

The color-alone task was identical to that in Experiment 1. The letter-alone task was similar, with 25 practice trials followed by two blocks of 50 experimental trials. At the outset, the letter was exposed for 200 ms. After every 25 trials, the exposure duration for the letter was decreased by 20 ms if the proportion correct in those 25 trials was greater than or equal to 0.80; the exposure was increased by 20 ms if the proportion correct was less than or equal to 0.60. For every participant, this procedure resulted in a final exposure duration of 100 ms, the minimum possible given the number of trials. The dual task was also similar to Experiment 1 except that participants were instructed not to hurry their response to Task 2, the letter identification. Instead, they were encouraged to make their responses as accurate as possible. They were instructed to make their response to Task 1, the color discrimination, as quickly as possible. There were 32 practice trials followed by three blocks of 64 experimental trials. The initial exposure duration for the letter was the final duration from the letter-alone task, which was 100 ms for all participants. The duration was also adjusted every 32 trials during the dual task. If the proportion correct was more than 0.80, the duration was decreased by 20 ms; if it was less than 0.70, it was increased by 20 ms. The lowest allowable exposure duration was 20 ms. Although the exposure duration changed during the task, duration was not confounded with SOA in any way because all SOAs occurred equally often in each set of 32 trials.

Results

Color-Alone Task

RTs for color discrimination were significantly shorter for younger adults ($M = 414$ ms) than for older adults ($M = 543$ ms), $F(1, 38) = 29.57$, $p < .001$, $MSE = 5{,}721.20$. The

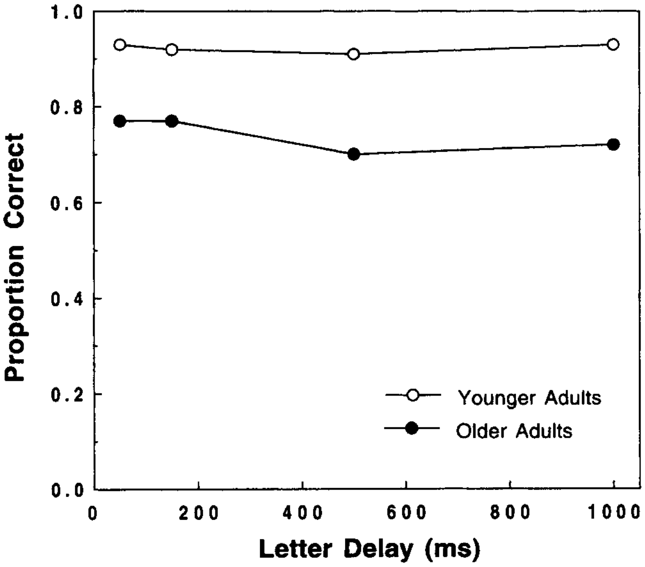

Figure 8. Mean proportion correct on Task 2 as a function of letter delay for younger and older adults in Experiment 2.

proportion correct was higher for younger adults (*M* = 0.96) than for older adults (*M* = 0.91), although not significantly, *F*(1, 38) = 0.42, *ns*, *MSE* = 0.01.

Letter-Alone Task

The duration of the letter was adjusted after every 25 trials. As noted, the final duration for all participants was 100 ms. The overall mean proportion correct on experimental trials for younger adults was 0.97; for older adults, it was 0.96. This difference was not significant, *F*(1, 38) = 0.03, *ns*, *MSE* < 0.01. The reaction times did differ significantly, with younger adults (*M* = 385 ms) faster than older adults (*M* = 493 ms), *F*(1, 38) = 24.89, *p* < .001, *MSE* = 4,800.00.

Dual Task

Task 2. The final exposure duration for the letters was lower for younger adults (*M* = 20 ms) than for older adults (*M* = 50 ms; *Mdn* = 20 ms), *F*(1, 38) = 8.25, *p* = .007, *MSE* = 9,219.51. Mean Task 2 accuracies (ACC2s) are given in Figure 8. An ANOVA was carried out on the ACC2s with age group as a between-subjects variable and SOA as a within-subjects variable. There was a significant effect of age group but not of SOA or of the interaction of age group and SOA: For age group, *F*(1, 38) = 20.36, *p* < .001, *MSE* = 0.05; for SOA, *F*(3, 114) = 2.84, *p* = .10, *MSE* < .01; for the interaction, *F*(3, 114) = 2.76, *p* = .11, *MSE* < .01. (Both SOA and the interaction were significant before the Greenhouse-Geisser correction; for both, *p* = .05.) ACC2 was noticeably lower for older adults (*M* = 0.74) than for younger adults (*M* = 0.92). For younger adults, ACC2 was relatively unaffected by SOA; for older adults, it was somewhat higher at the two shortest SOAs than at the two longest SOAs.

Task 1. Mean RT1s in the color task are given in Figure 9. An ANOVA in the RT1s showed significant effects of age group and SOA: For age group, *F*(1, 38) = 6.91, *p* = .01, *MSE* = 174,381.62; for SOA, *F*(3, 114) = 9.65, *p* < .001, *MSE* = 6,432.38. The interaction was not significant, *F*(3, 114) = 0.20, *ns*, *MSE* = 6,432.38. As in Experiment 1, older adults were slower and RT1s increased as the SOA decreased. An ANOVA on the proportion correct yielded a significant effect of age group but not of SOA or their interaction: For age group, *F*(1, 38) = 17.72, *p* < .001, *MSE* = 0.13; for SOA, *F*(3, 114) = 3.40, *p* = .08, *MSE* = 0.06; for the interaction, *F*(3, 114) = 0.48, *ns*, *MSE* = 0.06. As can be seen in Table 2, there was no systematic relationship between SOA and the proportion correct. The proportion of correct responses was very low, particularly for older adults (*M* = 0.66), much lower than for the color task done alone. Because a maximum of 1,500 ms was allowed for the color response and responses not made within that time were treated as errors, withholding the color response and grouping it with the letter response could have produced such timeout errors. The instruction not to hurry the response to the letter would have exaggerated this effect. An ANOVA on the proportion of trials with timeout errors on Task 1 showed only a significant effect of age group, *F*(1, 38) = 10.18, *p* = .003, *MSE* = 0.13. The effect of SOA and the interaction of age group and SOA were not significant: For SOA, *F*(3, 114) = 2.19, *p* = .15, *MSE* = 0.02; for the interaction, *F*(3, 114) = 2.28, *p* = .14, *MSE* = 0.02. The proportion of trials on which the participant failed to respond to the color was considerably higher in older adults (*M* = 0.31) than in younger adults (*M* = 0.13). Table 2 gives the overall proportion correct as well as the mean proportion of timeout errors for each age group and SOA. When the proportion correct was adjusted for timeout errors, accuracy varied little across the SOAs.

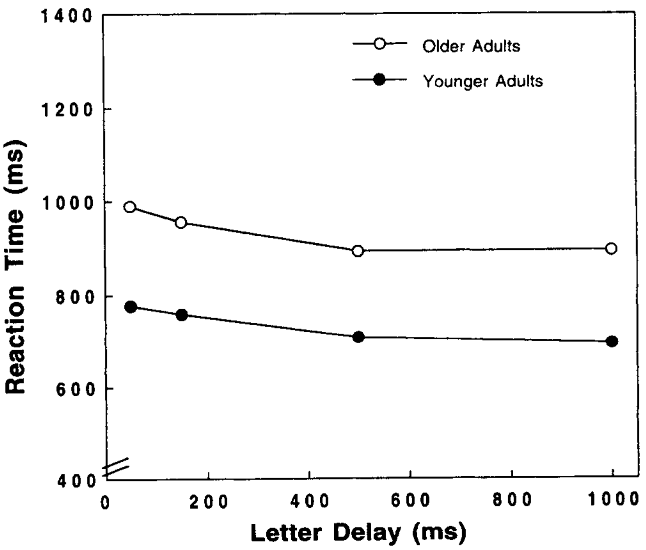

Figure 9. Mean Task 1 reaction time as a function of letter delay for younger and older adults in Experiment 2.

Dependencies between Task 2 and Task 1. An analysis similar to that in Experiment 1 was carried out to determine whether ACC2 on a trial was affected by whether the RT1 on that trial was in the fastest, middle, or slowest tertile of the RT1 distribution. Again, the effects that are added to the prior analysis of ACC2 are those involving tertile and interactions of tertile with age group and SOA. None of those effects approached significance; the largest *F* was 1.06 for the main effect of tertile. The mean RT2s are shown in Figure 10.

Discussion

Dual-Task Costs

A comparison of color-discrimination performance in the color-alone task and in longest SOA for the dual task again shows dual-task costs independent of any overlap in the two tasks. Even after correcting for timeout errors, accuracy dropped from the color-alone task to the color dual task at 1,000-ms SOA; the proportion correct dropped from 0.96 to 0.91 for younger adults and from 0.91 to 0.80 for older adults. Performance on the letter task is not directly comparable because adjustment of the exposure duration continued throughout the dual task.

Assessment of the Models

The task-switching model correctly predicted that, once the requirement for a speeded response had been removed, performance on Task 2 would be independent of the SOA: There was no significant effect of SOA on the proportion of correct responses. The capacity-sharing model predicted a decrease in accuracy at the shortest SOAs; the pattern of means was the opposite, particularly for older adults, with the greatest accuracy at the shortest SOAs. As in Experiment 1, RT1s increased with decreasing SOA, consistent with the capacity-sharing model but inconsistent with the task-switching model. Nevertheless, the interaction of age group and SOA for RT1 predicted by the capacity-sharing model was not found. There was, however, clear evidence of response grouping. Failures to respond to Task 1 within the allotted time were common, particularly in the older group. In the color-alone task, accuracy was high and, even in the older group, mean RT was only 36% of the 1,500 ms allotted for color response both in the color-alone task and in the dual task. Thus, failures to respond are very likely indications of withholding the color response until processing of the letter is nearly complete. The proportion of timeout errors would underestimate the actual proportion of trials with response grouping for younger adults and for the shortest SOAs because, for those individuals and conditions, even the withheld response could beat the deadline.

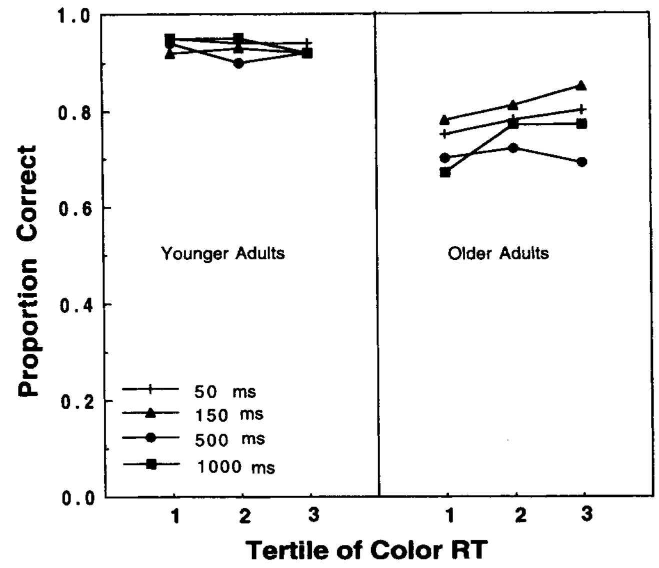

Figure 10. Mean Task 2 proportion correct as a function of letter delay and fastest, middle, or slowest third (tertile) of Task 1 reaction times (RTs) for younger and older adults in Experiment 2.

Table 2
Proportion Correct, Timeout Errors, and Adjusted Proportion Correct in Experiment 2

SOA (ms)	Raw proportion correct		Proportion timeout errors		Adjusted proportion correct	
	Younger	Older	Younger	Older	Younger	Older
50						
M	.86	.60	.09	.34	.95	.94
SD	.12	.32	.12	.22		
150						
M	.89	.68	.07	.29	.96	.97
SD	.12	.24	.11	.25		
500						
M	.85	.68	.12	.30	.97	.98
SD	.18	.24	.18	.28		
1,000						
M	.77	.62	.23	.31	1.00	.93
SD	.30	.23	.32	.26		

Note. SOA = stimulus onset asynchrony.

With the requirement for a speeded response to Task 2 removed, the task-switching model predicts that performance on Task 2 will not depend on Task 1 performance on a trial. Because the competition for the response-selection mechanism has been removed, Task 1 does not create a bottleneck that affects Task 2 performance. The analysis of dependencies confirmed this prediction. The capacity-sharing model would continue to predict a direct relationship between ACC2 and RT1 at all SOAs.

The weight of the evidence to this point leans against the capacity-sharing model and for a task-switching model combined with response grouping. Older adults may find the dual task more demanding, and their greater use of the strategy of grouping responses may be an attempt to reduce those demands, but there is no evidence for a fixed capacity that is shared between the two tasks and that is lower in older adults.

Experiment 3

In Experiments 1 and 2, both tasks required a keypress response. Even though the responses were given by different hands, controlled by different brain hemispheres, they were functionally highly similar. Simultaneous activation of similar responses in homologous structures may produce outcome conflict (Kinsbourne & Hicks, 1978; Navon & Miller, 1987). The difficulty of producing two very similar responses may have influenced participants to adopt a strategy of grouping their responses. If this was the case, changing the procedure so that the responses to the two tasks are quite different may reduce the incentive to group responses and, so, provide a cleaner test of the task-switching and capacity-sharing models. This was done in Experiment 3. The dual tasks in Experiment 3 replicated Experiments 1 and 2 but required a vocal rather than a keypress response for Task 2. There were two dual-task conditions: The *simultaneous dual task* replicated Experiment 1 with a speeded response to Task 2; the *sequential dual task* replicated Experiment 2 with the requirement for speed removed.

Method

Participants

There were 20 younger and 20 older adults drawn from the same population as the previous experiments. Their characteristics are given in Table 1. All participants completed both the simultaneous and sequential dual tasks.

Design and Procedure

Color-alone task. The color-alone task was identical to that in Experiment 1.

Letter-alone task. The letter-alone task was similar to that in Experiment 2. One important change was that the participant identified the letter by naming it aloud, speaking into a microphone held close to the mouth with the right hand. A voice-operated relay sensed the response and stopped the RT clock. Responses were tape recorded and reviewed later for correctness. There was one block of 20 practice trials followed by three blocks of 40 experimental trials, with rest permitted after each block. After every 20 trials, the duration was adjusted downward by 20 ms if the proportion correct on those 20 trials had been 0.80 or higher; it was adjusted upward by 20 ms if the proportion correct had been 0.60 or lower.

Simultaneous dual task. The simultaneous dual-task procedures were similar to Experiment 1 except that the participant first identified the color with a left-hand keypress and then identified the letter by naming it aloud. The participant was instructed to give each response as quickly as possible. The letter was exposed for 150 ms.

Sequential dual task. The sequential dual-task procedures were similar to Experiment 2 except that, as in the simultaneous dual task, the participant gave a verbal response to the letter. The participant was instructed to give the keypress response to the color as quickly as possible but not to hurry the response to the letter. The initial value of the exposure duration for the letters was the final value from the letter-alone task. In the sequential dual task, accuracy was evaluated every 16 trials. If 13 or more trials were correct, exposure duration was decreased by 20 ms (with a minimum exposure duration of 20 ms); if 11 or fewer were correct, exposure duration was increased by 20 ms.

The color-alone and letter-alone tasks were administered first, in that order. The simultaneous and sequential dual tasks were administered next, and the order of the tasks was counterbalanced across participants.

Results

Color-Alone Task

The keypress RTs were significantly slower for older adults (M = 503 ms) than for younger adults (M = 442 ms), $F(1, 38) = 9.87$, $p = .003$, $MSE = 3{,}373.32$. Accuracy did not differ in the two groups, $F(1, 38) = 0.02$, *ns*, $MSE < .01$; the mean proportion correct was 0.98 for younger adults and 0.97 for older adults.

Letter-Alone Task

The voice RTs were nearly identical for younger adults (M = 458 ms) and for older adults (M = 450 ms), $F(1, 38) = 0.02$, *ns*, $MSE < .01$. The proportion correct was also identical, 0.97 for both groups, $F(1, 38) = 0.00$, *ns*, $MSE < .01$.

Simultaneous Dual Task

Task 2. Mean RT2s are shown in Figure 11. An ANOVA on RT2s yielded only a significant main effect of SOA, $F(3, 114) = 41.95$, $p < .001$, $MSE = 19{,}771.63$. RT2s increased with decreasing SOA. Neither the main effect of age group nor the interaction of age group and SOA were significant: For age group, $F(1, 38) = 2.74$, $p = .11$, $MSE = 67{,}517.67$; for the interaction, $F(3, 114) = 0.50$, *ns*, $MSE = 19{,}771.63$. Older adults were slower at each SOA, but the age group differences were not significant. Analysis of ACC2s showed only a significant main effect of age group, $F(1, 38) = 7.76$, $p = .008$, $MSE = 0.03$. Neither the effect of SOA nor the interaction of age group and SOA were significant: For SOA, $F(3, 114) = 2.01$, $p = .12$, $MSE < .01$; for the interaction, $F(3, 114) = 0.65$, *ns*, $MSE < .01$.

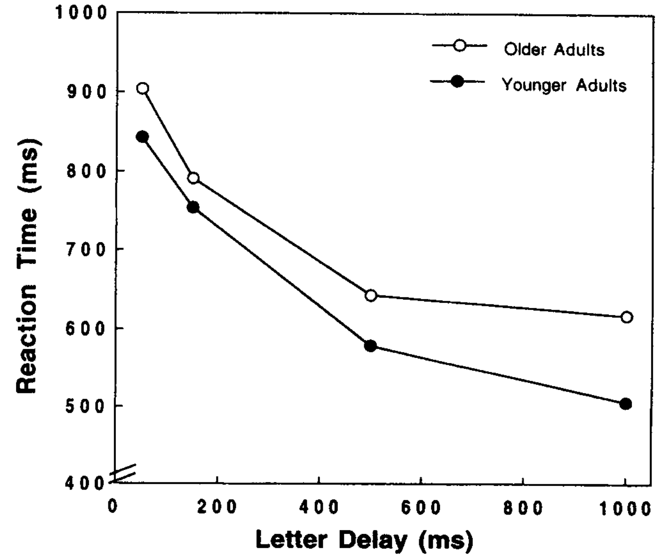

Figure 11. Mean Task 2 reaction time as a function of letter delay for younger and older adults in Experiment 3 with instructions to perform the tasks simultaneously.

Task 1. Mean RT1s are shown in Figure 12. An ANOVA on RT1s yielded no significant effects: For age group, $F(1, 38) = 3.59$, $p = .07$, $MSE = 49{,}906.89$; for SOA, $F(3, 114) = 2.22$, $p = .07$, $MSE = 1{,}153.88$; for the interaction, $F(3, 114) = 2.07$, $p = .07$, $MSE = 1{,}153.88$. As can be seen in Figure 12, SOA had little effect on RT1. An ANOVA on ACC1s produced a significant main effect of SOA and a significant interaction of age group and SOA: For SOA, $F(3, 114) = 10.02$, $p < .001$, $MSE < .01$; for the interaction, $F(3, 114) = 4.78$, $p = .005$, $MSE < .01$. The main effect of age group was not significant, $F(1, 38) = 0.29$, *ns*, $MSE < .01$. Accuracy for younger adults was slightly lower at the shortest SOA; for older adults, accuracy was uniform across SOAs.

Analyses were also carried out on the proportions of timeout errors and long RTs (RTs between 1,000 and 1,500 ms) in Task 1. There were no significant effects in either analysis. Younger adults committed timeout errors on 0.52% of the trials, and older adults committed timeout errors on 1.00%. Younger adults had long RTs on 3.05% of the trials and older adults had long RTs on 4.71%.

Dependencies between Task 1 and Task 2. An ANOVA on RT2 with tertile of RT1 as an additional factor produced a significant main effect of tertile and a significant interaction of SOA and tertile: For tertile, $F(2, 76) = 117.26$, $p < .001$, $MSE = 13{,}785.32$; for the interaction, $F(6, 228) = 14.23$, $p < .001$, $MSE = 7{,}326.59$. Neither the interaction of age group and tertile nor the three-way interaction of age group, SOA, and tertile approached significance (both Fs < 1). The means are shown in Figure 13. Once again, RT2s increased with longer RT1s for the short SOAs, but the two were relatively independent at the longest SOAs.

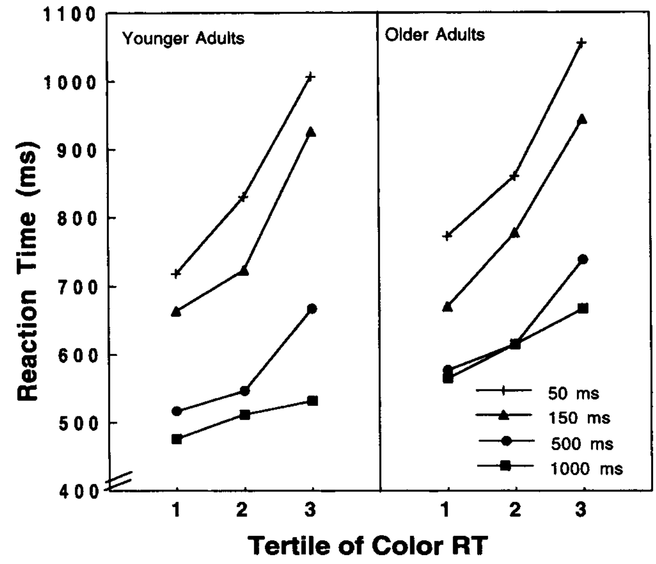

Figure 13. Mean Task 2 reaction time (RT) as a function of letter delay and fastest, middle, or slowest third (tertile) of Task 1 RTs for younger and older adults in Experiment 3 with instructions to perform the tasks simultaneously.

Sequential Dual Task

Task 2. The final adjusted exposure duration for all 40 individuals was 20 ms. Mean Task 2 accuracies (ACC2s) are given in Figure 14. An ANOVA was carried out on the ACC2s with age group as a between-subjects variable and SOA as a within-subjects variable. There was a significant

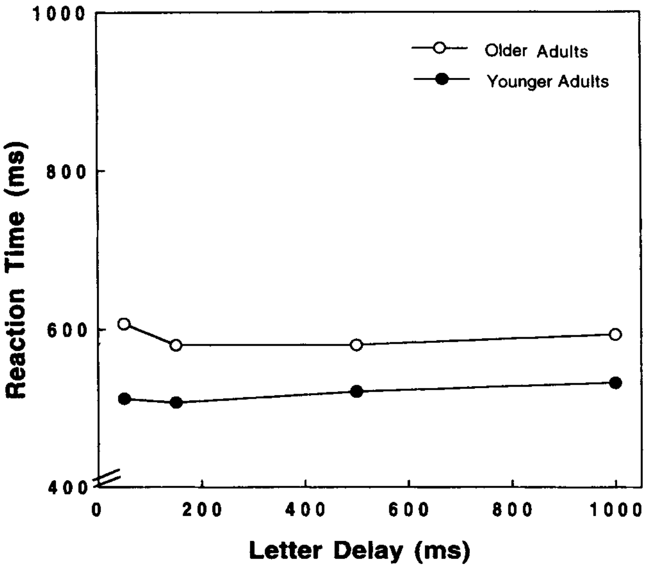

Figure 12. Mean Task 1 reaction time as a function of letter delay for younger and older adults in Experiment 3 with instructions to perform the tasks simultaneously.

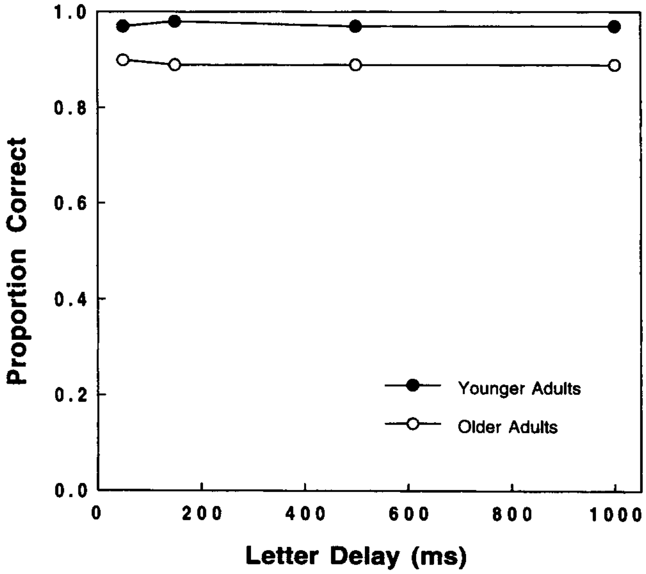

Figure 14. Mean Task 2 proportion correct as a function of letter delay for younger and older adults in Experiment 3 with instructions to perform the tasks sequentially.

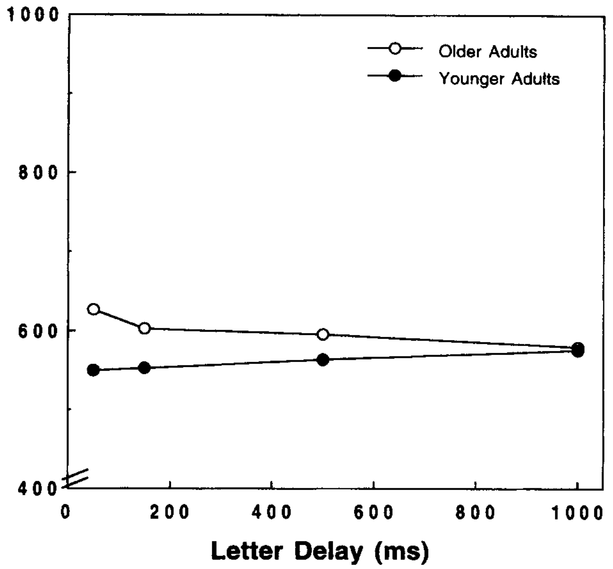

Figure 15. Mean Task 1 reaction time as a function of letter delay for younger and older adults in Experiment 3 with instructions to perform the tasks sequentially.

effect of age group but not of SOA or of the interaction of age group and SOA: For age group, $F(1, 38) = 7.71$, $p = .008$, $MSE = 0.03$; for SOA, $F(3, 114) = 0.20$, *ns*, $MSE < .01$; for the interaction, $F(3, 114) = 0.55$, *ns*, $MSE < .01$. ACC2 was lower for older adults ($M = 0.89$) than for younger adults ($M = 0.97$). In both age groups accuracy was completely unaffected by SOA.

Task 1. Mean RT1s in the color task are given in Figure 15. An ANOVA in the RT1s showed a significant interaction of age group and SOA, $F(3, 114) = 4.05$, $p = .009$, $MSE = 2{,}149.97$. Neither the main effect of age group nor SOA was significant: For age group, $F(1, 38) = 0.84$, *ns*, $MSE = 73{,}197.13$; for SOA, $F(3, 114) = 0.46$, *ns*, $MSE = 2{,}149.97$. For the younger adults, RT1s increased by 26 ms from the shortest to the longest SOA; for the older adults, RT1s decreased by 47 ms. Separate ANOVAs for each age group showed that the effect of SOA was not significant for the younger adults, $F(3, 57) = 1.07$, $p = .37$, $MSE = 2{,}871.22$; it was significant for the older adults, $F(3, 57) = 4.05$, $p = .015$, $MSE = 1{,}212.17$. An ANOVA on the ACC1s yielded no significant effects: For age group, $F(1, 38) = 0.30$, *ns*, $MSE = 0.06$; for SOA, $F(3, 114) = 0.96$, *ns*, $MSE = 0.01$; for the interaction, $F(3, 114) = 0.83$, *ns*, $MSE = 0.01$. There was almost no difference between younger ($M = 0.92$) and older adults ($M = 0.91$), and accuracy was unaffected by SOA. The Task 1 data were analyzed for timeout errors and for long RTs. There were no significant effects. Timeout errors occurred on 4.13% of the trials for younger adults and 3.36% of the trials for older adults; long RTs occurred on 5.91% of the trials for younger adults and 5.57% of the trials for older adults.

Dependencies between Task 2 and Task 1. An analysis identical to that in Experiment 2 was carried out to determine whether ACC2 on a trial was affected by whether that RT1 on that trial was in the fastest, middle, or slowest tertile of the RT1 distribution. Again, the effects that are added to the prior analysis of ACC2 are those involving tertile and interactions of tertile with age group and SOA. None of those effects approached significance: all Fs < 1.0. The mean RT2s are shown in Figure 16.

Discussion

Dual-Task Costs

Again there were costs to performing each of the tasks in the dual-task context instead of alone, even at the longest SOA, when the response to Task 1 would most likely have been given before the Task 2 stimulus appeared. Color RTs were 90 ms slower for both younger and older adults in the simultaneous dual task at 1,000-ms SOA than in the color-alone task (532 ms compared with 442 ms and 593 ms compared with 503 ms, respectively). They were 133 ms slower for younger adults and 77 ms slower for older adults in the sequential dual task (576 ms compared with 442 ms and 580 ms compared with 503 ms, respectively). Letter RTs were 49 ms slower for younger adults and 168 ms slower for older adults in the simultaneous dual task at the 1,000-ms SOA task (506 ms compared with 457 ms and 618 ms compared with 450 ms, respectively). Because exposure durations for the letters were adjusted throughout the letter-alone task, letter RTs in the dual task are not comparable to those in the letter-alone task.

Task 2

In the simultaneous dual task, both models predicted that the time to carry out the second task, letter identification,

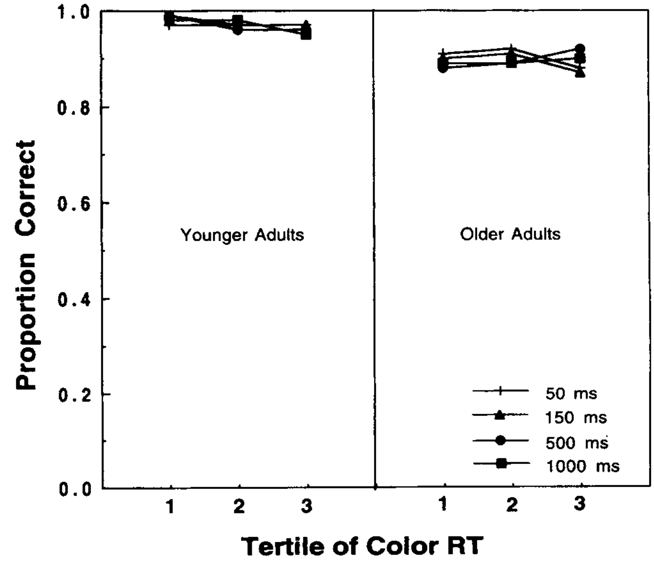

Figure 16. Mean Task 2 proportion correct as a function of letter delay and fastest, middle, or slowest third (tertile) of Task 1 reaction times (RTs) for younger and older adults in Experiment 3 with instructions to perform the tasks sequentially.

would increase as the SOA was reduced; they also predicted that the effects of age group would be overadditive with the effects of SOA. Only the first of these predictions was confirmed. There was no sign of the overadditive interaction of age group and SOA found in Experiment 1. It might be argued that, because there was no age difference in RT2, no interaction would be expected. The absence of a significant age difference in RT2 is unusual but not surprising. Absences of age differences in RT for voice responses have been reported previously (Nebes, 1978). In the sequential dual task, the task-switching model predicted that removing the competition for the response-selection mechanism should open the bottleneck and eliminate dual-task interference. This was observed. Accuracy on the second task was unaffected by SOA in either age group. In contrast, the capacity-sharing model predicted incorrectly that there would be a decrease in accuracy at short SOAs and that the decrease should be even greater in older adults.

Task 1

The task-switching model predicted that the time to carry out the first task, color identification, would be independent of SOA whether the tasks were carried out simultaneously or sequentially because the first task would have the initial claim on the response-selection mechanism. In the capacity-sharing model, dual-task interference affects both tasks when they overlap, so Task 1 performance should have been progressively more impaired as SOA was decreased, particularly for older adults. Overall, Task 1 performance was relatively independent of SOA. There was one anomaly. In older adults in the sequential task, RT increased slightly but significantly at the shortest SOA. Although it fell short of significance, there was a very similar pattern in the simultaneous task.

Dependencies Between Task 1 and Task 2

The task-switching model predicted that, at short SOAs, performance in the second task would be more impaired the slower the first task was completed in the simultaneous dual task but that the two would be independent at long SOAs and in the sequential dual task. These predictions were confirmed. The capacity-sharing model predicted a positive relationship between RT2 or ACC2 and RT1 in both versions of the dual task and at all SOAs; this prediction was not confirmed.

Assessment of the Models

The weight of the evidence favors the task-switching model. The most parsimonious interpretation is that both younger and older adults are best described by a task-switching model with the added assumption that older adults are simply slower to carry out all stages of processing.

The rationale for Experiment 3 was that at least some of the dual-task interference in Experiments 1 and 2 may have been due to outcome conflict. The demands of organizing and emitting two highly similar motor responses may have induced a strategy of grouping the responses. Grouping could have produced results that gave the appearance, artifactually, of capacity sharing. In Experiment 3, the two responses were in different modalities: a keypress response to Task 1 and a verbal response to Task 2. The decision components of the two tasks were exactly the same, so the only change was reduce the functional similarity of the responses to be given. This change virtually eliminated evidence of response grouping. Despite the elimination of response grouping, there was an increase in Task 1 RTs at short SOAs for the older adults. The increase was significant in the sequential condition and approached significance in the simultaneous condition. Because it occurred even in the simultaneous task, when the response in Task 2 could be delayed, and because there was no evidence that it was due to response grouping, this is consistent with a sharing of capacity between the two tasks in older adults.

Experiment 4

In the task-switching model, when two tasks overlap, perceptual identification (or, more generally, early stages that precede response selection) in the two tasks can proceed in parallel (see Figure 3). Once perceptual identification in Task 2 is complete, processing must be postponed until response selection is completed in Task 1 and the mechanism is switched over to Task 2. There is unused time in the processing of Task 2. The task-switching model makes the surprising prediction that, at short SOAs, the perceptual difficulty of Task 2 can be increased without affecting overall Task 2 performance (see, e.g., Pashler, 1994a, p. 224, Principle 3). The effect of the additional difficulty can be absorbed in the unused time. More generally, the model predicts an underadditive interaction of SOA and the perceptual difficulty of Task 2: The effect of difficulty should be greater at long SOAs than at short SOAs. This prediction has been confirmed repeatedly (Pashler, 1984, 1991; Pashler & Johnston, 1989). Experiment 4 examined the effect of increasing perceptual difficulty in both younger and older adults. With the assumption that older adults are generally slower, the task-switching model predicts that, although there will be an overadditive interaction of age group and SOA, both age groups will show the underadditive interaction of perceptual difficulty and SOA. The capacity-sharing model postulates that resources must be shared any time two tasks overlap. A more difficult task will be more affected by sharing resources than a less difficult task, so the effects of task difficulty should be exacerbated by increasing overlap. Reduced resources in older adults would further exaggerate the effect. The prediction of the capacity-sharing model, then, is in sharp contrast to that of the task-switching model: There should be an overadditive interaction of task difficulty and SOA and, in addition, an overadditive interaction of age group, task difficulty, and SOA.

The difficulty of Task 2, the letter identification, was varied by reducing the discriminability of the letter from the background. The color was presented as a patch. The letter appeared in the patch in the same color, differing only in the saturation. In the easy discrimination, the letter was presented in black (i.e., completely desaturated) against a saturated surround. In the hard discrimination, the letter was nearly as saturated as the surround, appearing only slightly darker.

Method

Participants

The 20 younger and 20 older adults were drawn from the same populations as in the previous experiments. Their characteristics are given in Table 1.

Design and Procedure

There were five tasks, described below in the order in which they were administered.

Color-alone task. In this task a colored patch, red or green, was presented at the center of the display on each trial, and the participant responded with a left-hand keypress, *z* for red and *x* for green. Each trial began with a white patch on a dark background. After 500 ms, the color of the patch was changed to red or green for 200 ms and was then changed back to white. The participant was allowed 1,500 ms from the onset of the red or green color to respond. There were 25 practice trials followed by 100 experimental trials.

Letter-alone task. Each trial began with the presentation of a white patch at the center of the display containing a black *X*. After 500 ms, the *X* was replaced by an *A* or a *B*, also in black. After 200 ms, the *A* or *B* was replaced by an *X*. The participant was allowed 5,000 ms from the onset of the *A* or *B* to respond by pressing the period key for A or the slash key for B. There were 25 practice trials followed by 100 experimental trials.

Easy-discrimination dual task. Each trial began with the presentation of a white patch containing a black *X* at the center of the display. After 500 ms, the color of the patch was changed to red or green. Then, after an SOA of 50, 150, 500, or 1,000 ms, the *X* was replaced with an *A* or *B*, also in black. After 200 ms, the display was replaced with a white patch containing a black *X*. From the onset of the red or green, 1,500 ms were allowed to respond to the color by pressing the *z* (red) or *x* (green) key. After the onset of the *A* or *B*, 5,000 ms were allowed to respond to the letter by pressing period (*A*) or slash (*B*). Participants were instructed to respond as quickly as possible to each of the component tasks. Errors and failures to respond in the allotted time were signaled by tones, a high tone for the color task and a low tone for the letter task. There were 16 practice trials followed by 192 experimental trials, with rest breaks allowed after 64 and 128 trials. Each SOA was represented equally often in each set of 16 trials.

Color-adjustment task. This task was similar to the letter-alone task except that the letters, *A* or *B*, were presented on a colored patch, red or green. The participants again responded by pressing period (*A*) or slash (*B*). The letters were a desaturated version of the color of the patch. The MEL color palette provides 64 steps of saturation between fully desaturated (0) and fully saturated (63). Every color is a combination of red, green, and blue with a saturation specified for each. For example, a fully saturated red is ⟨63,0,0⟩ and a fully saturated green is ⟨0,63,0⟩. These colors were used for the color patches. At the outset, the letters were presented at a saturation of 28, appearing a very dark green or red. The saturation was adjusted after every tenth trial. If there had been no errors in the preceding 10 trials, the letter saturation was increased by 2 units (making the letter more similar to the background); if there were two or more errors, the saturation was decreased by 2 units (making the letter less similar to the background).

Hard-discrimination dual task. This task was identical to the easy-discrimination dual task except that the final value from the color-adjustment task was used for the letters.

Display

Typical viewing distance was 46 cm, although the participant's position was not restrained. The white and colored patches were 12.5 mm horizontally × 16 mm vertically or about 1.56° × 1.99°. As before, the letters *X* and *A* were 10 mm in width × 12 mm in height or about 1.25° × 1.49°; the letter *B* was 8 mm × 12 mm or about 1.00° × 1.49°.

Results

Color-Alone Task

RT to identify the color of the patches was significantly greater in older adults (M = 500 ms) than in younger adults (M = 433 ms), $F(1, 38) = 10.20$, $p = .003$, $MSE = 4{,}724.05$. There was no significant difference in the proportion correct for younger (M = 1.00) and older (M = 0.95) adults, $F(1, 38) = 1.06$, $p = .31$, $MSE = 0.02$.

Letter-Alone Task

RT to identify the letters was significantly greater in older adults (M = 462 ms) than in younger adults (M = 409 ms), $F(1, 38) = 7.91$, $p = .008$, $MSE = 3{,}814.84$. There was no significant difference in the proportion correct for younger (M = 0.97) and older (M = 0.96) adults, $F(1, 38) = 0.64$, *ns*, $MSE < .01$.

Color-Adjustment Task

An analysis of the final value of the saturation for the letter color showed no difference between younger adults (M = 48.60) and older adults (M = 47.40), $F(1, 38) = 0.50$, *ns*, $MSE = 14.40$.

Dual Task

Task 2. Mean RT2s for both the easy-discrimination and hard-discrimination dual tasks are shown in Figure 17. An ANOVA was carried out on the RT2s with age group as a between-subjects variable and discrimination (easy and hard) and SOA (50, 150, 500, and 1,000 ms) as within-subjects variables. There were significant main effects of age group, discrimination, and SOA: For age group, $F(1, 38) = 10.66$, $p = .002$, $MSE = 150{,}233.75$; for SOA, $F(3, 114) = 459.84$, $p < .001$, $MSE = 7{,}257.60$; for discrimination, $F(1, 38) = 44.33$, $p < .001$, $MSE = 18{,}028.56$. As can be seen in Figure 17, older adults were slower than younger adults, RT2s increased with decreasing SOA, and RT2s were greater in the hard-discrimination task than in the easy-discrimination task. There were significant two-way interactions of age group and SOA and discrimination and SOA: For age group and SOA, $F(3, 114) = 3.40$, $p = .045$, $MSE = 7{,}527.60$; for discrimination and SOA, $F(3, 114) = 14.34$,

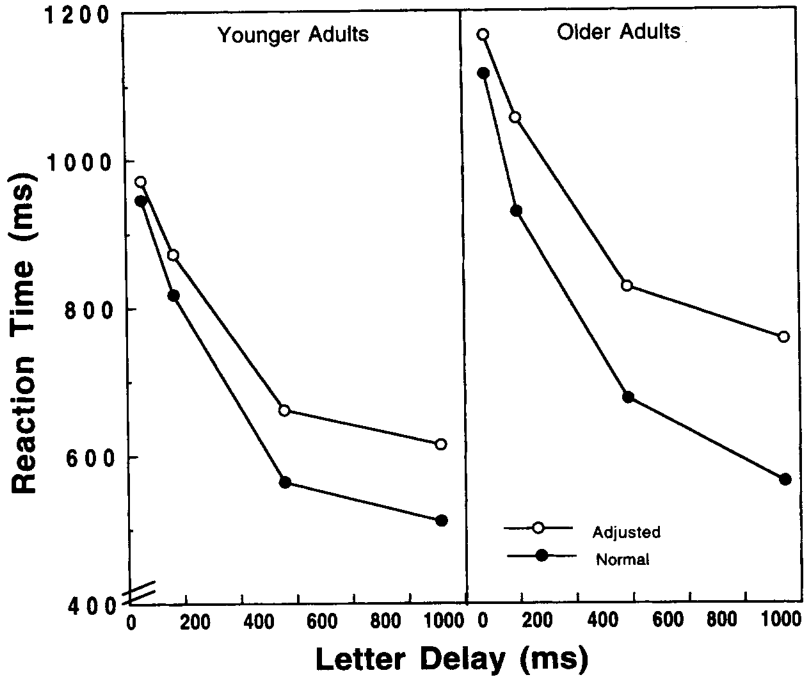

Figure 17. Experiment 4: Mean Task 2 reaction time as a function of age group and letter delay for easy (normal color) and hard (adjusted color) discrimination versions of Task 2.

$p < .001$, $MSE = 3{,}102.07$. The interaction of age group and SOA was overadditive: Older adults were slower than younger adults by 98 ms at 1,000-ms SOA but were slower by 182 ms at 50-ms SOA. The interaction of discrimination and SOA was underadditive: The hard discrimination slowed RT2s by 147 ms at the longest SOA but slowed them by only 38 ms at the shortest SOA. The interactions of age group and discrimination, $F(3, 114) = 3.92$, $p = .055$, $MSE = 18{,}028.56$, and of age group, discrimination, and SOA, $F(3, 114) = 1.16$, $p = .33$, $MSE = 3{,}102.07$, were not significant.

Analyses of the ACC2s showed only significant interactions of age group and discrimination and discrimination and SOA: For age group and discrimination, $F(1, 38) = 14.52$, $p < .001$, $MSE < .01$; for discrimination and SOA, $F(3, 114) = 5.64$, $p = .003$, $MSE < .01$. Younger adults were slightly more accurate in the hard discrimination ($M = 0.94$) than in the easy discrimination ($M = 0.92$), whereas older adults were slightly more accurate in the easy discrimination ($M = 0.91$) than in the hard discrimination ($M = 0.90$). For SOA, accuracy was slightly higher in the hard task ($M = 0.92$) than in the easy task ($M = 0.90$) at the shortest SOA, but it was slightly lower in the hard task ($M = 0.88$) than in the easy task ($M = 0.91$) at the longest SOA.

To simplify the presentation, analyses of the dependencies between RT2 and RT1 are not reported for this and the subsequent experiments. They showed effects comparable to those in Experiment 1 and in the simultaneous condition of Experiment 3.

Task 1. The mean RT1s are shown in Figure 18. Analyses of the RT1s showed a significant main effect of SOA and significant interactions of discrimination and SOA and of age group, discrimination, and SOA: For SOA, $F(3, 114) = 18.63$, $p < .001$, $MSE = 3{,}195.70$; for discrimination and SOA, $F(3, 114) = 14.86$, $p < .001$, $MSE = 1{,}218.96$; for the three-way interaction, $F(3, 114) = 3.05$, $p = .044$, $MSE = 1{,}218.96$. As can be seen in Figure 18, RT1s increased with decreasing SOA in the easy-discrimination task; RT1s were less affected by SOA in the hard-discrimination task. Age differences were generally greater in the hard task than in the easy task, except at 500-ms SOA.

Analyses of the ACC1s showed significant interactions of age group with discrimination and of discrimination with SOA: For age group and discrimination, $F(1, 38) = 4.21$, $p = .047$, $MSE < .01$; for discrimination and SOA, $F(3, 114) = 7.07$, $p < .001$, $MSE < .01$. Younger adults were slightly more accurate in the hard discrimination ($M = 0.95$) than in the easy discrimination ($M = 0.94$), whereas older adults were more accurate in the easy discrimination ($M = 0.92$) than in the hard discrimination ($M = 0.91$). For SOA, accuracy in the easy discrimination was slightly higher at the two longest SOAs ($M = 0.94$) than at the two shortest SOAs ($M = 0.92$), whereas in the hard discrimination, accuracy was slightly higher at the two shortest SOAs ($M = 0.94$) than at the two longest SOAs ($M = 0.92$).

Analyses of timeout errors and long RTs in Task 1 showed only one significant effect, an interaction of age group and discrimination in the proportion of trials with timeout errors, $F(1, 38) = 5.45$, $p = .025$, $MSE < .01$. Older adults had a higher proportion than younger adults in the hard discrimination (Ms $= 0.06$ and 0.02, respectively), but the two groups

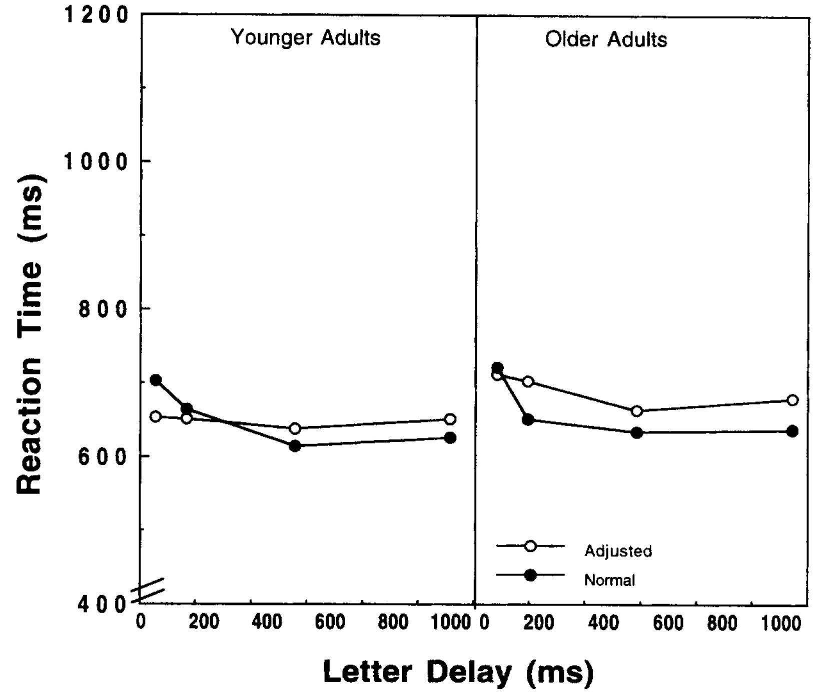

Figure 18. Experiment 4: Mean Task 1 reaction time as a function of age group and letter delay for easy (normal color) and hard (adjusted color) discrimination versions of Task 2.

were very similar in the easy discrimination (*M*s = 0.02 and 0.01, respectively).

Discussion

The important finding was the underadditive interaction of Task 2 difficulty and SOA: The effect of increasing the perceptual difficulty of Task 2 was less when the two tasks overlapped substantially than when they were well separated. The task-switching model predicted that this would occur because, at short SOAs, the additional time required for perceptual analysis in the hard discrimination could be absorbed into the time while Task 2 was waiting for Task 1 to free the response-selection mechanism. Both younger and older adults showed the underadditive interaction. These findings are clearly inconsistent with the model that holds capacity is shared between the two tasks and that capacity is reduced in older adults.

Both younger and older adults showed an increase in Task 1 RTs at short SOAs in the easy-discrimination condition. In Experiments 1 and 2, such results were attributed to response grouping. In this experiment, there was very little evidence that individuals in either group were withholding Task 1 responses; there was no evidence that the likelihood of withholding a response was related to the SOA. The effect occurred in the easy-discrimination condition but not in the hard-discrimination condition. The presentation of the Task 2 stimulus—the letter—in the easy-discrimination condition involves the sudden onset of high-contrast contours. This may have disrupted perceptual processing of Task 1, accounting for the increase in RT1s with decreasing SOA in the easy- but not the hard-discrimination task. In a sense, then, this would represent a shared capacity, but of a very particular kind.

Experiment 5

Another prediction of the task-switching model is that manipulating the duration of stages at or after response selection in Task 1 will have no effect on Task 1 performance and will slow Task 2 performance to the same extent at every SOA (see Pashler, 1994a, p. 224, Principle 4). That is, the effects of the manipulation on RT2 will be additive with those of SOA. Task 1 interferes with Task 2 to the extent that Task 2 must wait for the response-selection mechanism to be freed. Once the mechanism has been switched to Task 2, the two tasks can proceed independently. Any factor that affected Task 2 after the response-selection mechanism was switched would serve only to lengthen RT2; it would not affect RT1. The capacity-sharing model makes a very different prediction. Any factor that increases the difficulty of either task should increase interference, impairing both tasks. There should be an overadditive interaction with greater effects of the manipulation at short SOAs than at long SOAs. The existing evidence supports the prediction of the task-switching model (Fagot & Pashler, 1992; McCann & Johnston, 1992; Pashler, 1984, 1989; Pashler & Johnston, 1989).

Experiment 5 tested the prediction that effects of a factor increasing the difficulty of response selection in Task 2 would be additive with the effects of SOA. Response-selection difficulty was manipulated by increasing the number of Task 2 response alternatives from two to six. Task 2 was to identify a number by saying it aloud. As before, Task 1 was to identify a color by making a keypress.

Method

Participants

There were 20 younger and 20 older adults drawn from the same populations as the prior experiments. Their characteristics are given in Table 1.

Design and Procedure

Color-alone task. Each trial began with the presentation of a white rectangular outline box on a black background. After 500 ms, the color of the box was changed either to red or to green. After 200 ms, the color was changed back to white. The participant had a total of 1,500 ms from the onset of the color to respond by pressing the *z* key for green or the *x* key for red. The intertrial interval was 1,000 ms. There were 20 practice trials followed by 70 experimental trials.

Number-alone task. Each trial began with the presentation of a white rectangular outline box on a black background. After 500 ms, a number, 2 or 5, displayed in white, appeared in the box. The numbers resembled those in liquid crystal displays, consisting exclusively of vertical and horizontal segments. The number was erased after 200 ms; the box remained visible until a response was given or 1,300 ms additional had elapsed. The intertrial interval was 1,000 ms. The participant responded by naming the number aloud, speaking into a microphone held near the mouth with the right hand. Only two numbers were used in the number-alone task. It seemed possible that, if participants were exposed to all six numbers in practice, they might treat the dual-task trials as having six response alternatives even in the block that had only two choices.

Two-choice dual task. Each trial began with the presentation of a white rectangular outline box for 500 ms, after which the color was changed to green or to red. At an SOA of 50, 150, 500, or 1,000 ms after the color change, a number, 2 or 5, appeared in the box, in the same color as the box. The number was removed 200 ms after it appeared. In the color task, the participant had 1,500 ms from the onset of the color to respond with a keypress; in the number task, the participant had 2,000 ms from the onset of the number to respond by naming it aloud. The participant was instructed to respond to each task as quickly as possible but without making errors. There were 16 practice trials followed by three blocks of 36 trials, resulting in 27 experimental trials at each SOA.

Six-choice dual task. The six-choice dual task was identical to the two-choice dual task except that there were six possible numbers, 2, 3, 4, 5, 6, and 9. Again, the numbers resembled those in liquid crystal displays. The instructions explained that there would be six possible numbers and showed an example of each.

Each participant first completed the color-alone task and the number-alone task in that order. The dual tasks were completed next, and the order of the two dual tasks was randomly determined for each participant.

Display

As before, viewing distance was approximately 46 cm. The outline boxes were 11 mm wide and 27 mm high, subtending approximately 1.37° × 3.36°. The numbers were 7 mm × 15 mm, subtending approximately 0.88° × 1.88°.

Results

Color-Alone Task

Mean keypress RT to the color was 505 ms for the older adults and 478 ms for the younger adults; this difference was not significant, $F(1, 38) = 0.90$, *ns*, $MSE = 6{,}763.12$. There was also no difference in the proportion correct (for younger adults, $M = 0.97$; for older adults, $M = 0.95$), $F(1, 38) = 2.67$, $p = .11$, $MSE < .01$.

Number-Alone Task

Mean voice RT to the number was 612 ms for the younger adults and 642 ms for the older adults; this difference was not significant, $F(1, 38) = 1.59$, $p = .22$, $MSE = 4{,}486.40$. There was also no difference in the proportion correct (for younger adults, $M = 0.99$; for older adults, $M = 0.93$), $F(1, 38) = 2.67$, $p = .31$, $MSE = 0.03$.

Task 2

Mean RT2s are shown in Figure 19. An ANOVA was carried out on the RT2s with age group as a between-subjects variable and number of choices (2 and 6) and SOA (50, 150, 500, and 1,000 ms) as within-subjects variables. The ANOVA produced significant main effects of number of choices and of SOA: For number of choices, $F(1, 38) = 8.27$, $p = .007$, $MSE = 12{,}110.03$; for SOA, $F(3, 114) = 78.03$, $p < .001$, $MSE = 15{,}034.99$. Overall, two choices resulted in shorter RT2s ($M = 529$ ms) than did six choices ($M = 561$ ms). As can be seen in Figure 19, RT2 increased with decreasing SOA as in Experiments 1, 3, and 4. There were significant two-way interactions of age group and number of choices and of age group and SOA: For age group and number of choices, $F(1, 38) = 4.62$, $p = .039$, $MSE = 12{,}110.03$; for age group and SOA, $F(3, 114) = 6.39$, $p = .008$, $MSE = 15{,}034.99$. Increasing the number of choices slowed the younger adults by only 11 ms on average, whereas it slowed the older adults by 53 ms. RT2s increased more with decreasing SOA for the older adults than they did for the younger adults: The older adults were 3 ms faster on average at an SOA of 1,000 ms, whereas they were 139 ms slower at an SOA of 50 ms. The interaction most critical for testing the prediction of the task-switching model is that of number of choices and SOA; that interaction was not significant, $F(3, 114) = 0.11$, *ns*, $MSE = 4{,}925.29$.

Analysis of ACC2s showed a significant effect of SOA, $F(3, 114) = 4.74$, $p = .007$, $MSE < .01$, and a significant interaction of the number of choices and SOA, $F(3, 114) = 8.94$, $p < .001$, $MSE < .01$. The mean ACC2s are shown in Table 3. The interaction appears to be due to the drop in performance at the 500-ms SOA in the six-choice condition.

Task 1

Mean RT1s are shown in Figure 20. An ANOVA produced significant main effects of age group and number of choices: for age group, $F(1, 38) = 10.84$, $p = .003$, $MSE = 88{,}782.83$; for number of choices, $F(1, 38) = 13.47$, $p =$

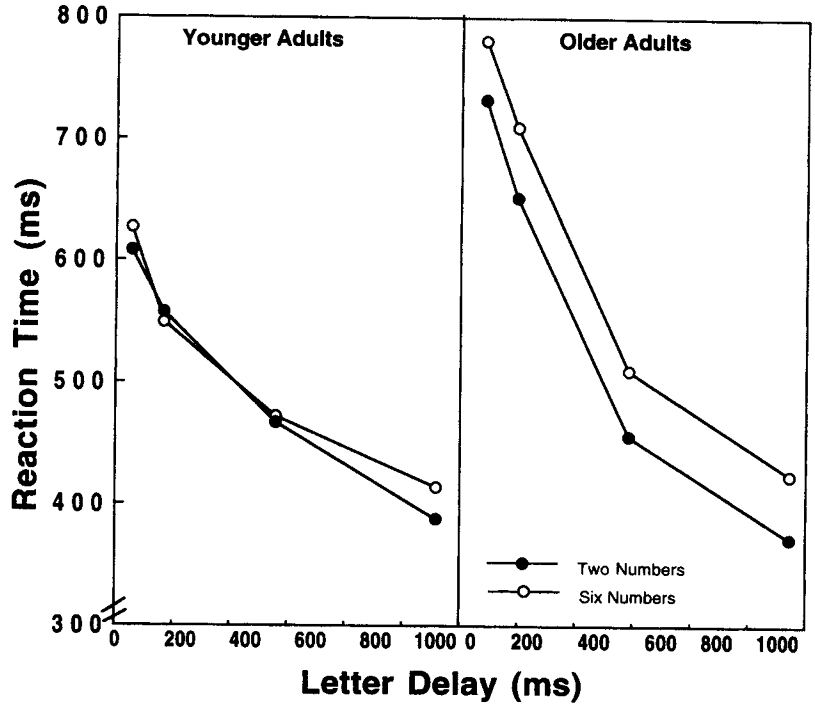

Figure 19. Experiment 5: Mean Task 2 reaction time as a function of age group and letter delay for two-choice and six-choice versions of Task 2.

.001, *MSE* = 2,310.02. Older adults (*M* = 547 ms) were slower than younger adults (*M* = 491 ms), and two choices in Task 2 produced longer RT1s (*M* = 564 ms) than did six choices (*M* = 542 ms). There was also a significant interaction of number of choices and SOA, *F*(3, 114) = 5.90, *p* = .001, *MSE* = 795.23, with RT1 1 ms faster for six choices than for two choices at 50-ms SOA but with RT1 36 ms slower for six than for two choices at 1,000-ms SOA. RT1s increased with increasing SOA for younger adults but not for older adults; the interaction of age group and SOA was nonsignificant with the Greenhouse-Geisser correction, *F*(3, 114) = 2.91, *p* = .093, *MSE* = 8,088.31, although it was significant in the conventional analysis (*p* = .039).

An ANOVA on ACC1s yielded a significant effect of SOA and a significant interaction of number of choices and SOA: For SOA, *F*(3, 114) = 4.74, *p* = .007, *MSE* < .01; for the interaction, *F*(3, 114) = 8.94, *p* < .001, *MSE* < .01. For SOAs of 50, 150, 500, and 1,000 ms, the mean ACC1s for two choices were 0.96, 0.93, 0.95, and 0.93, respectively, whereas for six choices the means were 0.93, 0.95, 0.86, and 0.91, respectively.

Analyses of timeout errors showed no significant effects, although older adults had a somewhat higher proportion (*M* = 0.03) than younger adults (*M* = 0.01). Similarly for long RT1s, older adults had a higher proportion (*M* = 0.11) than younger adults (*M* = 0.07), but there were no significant effects.

Table 3
Proportion Correct for Task 2 in Experiment 5

	Choices			
	2		6	
SOA (ms)	Younger	Older	Younger	Older
50				
M	.96	.95	.96	.96
SD	.03	.04	.06	.04
100				
M	.98	.96	.97	.98
SD	.02	.06	.04	.02
500				
M	.98	.96	.97	.98
SD	.03	.04	.03	.02
1,000				
M	.97	.95	.97	.98
SD	.04	.05	.04	.05

Note. SOA = stimulus onset asynchrony.

Discussion

The effect of increasing the difficulty of response selection in Task 2 on RT was additive with the effects of SOA, as the task-switching model predicted. The additivity was clearest in the older adults, although there was no sign in either age group of the overadditive interaction predicted by the capacity-sharing model. Similarly, RTs in Task 1 did not increase at the shortest SOAs, nor was there an overadditive interaction of the number of choices and SOA as the capacity-sharing model would predict. Increasing the difficulty of response selection in Task 2 did affect RTs in Task 1, but the result was lower RT1s for the more difficult version of Task 2. This was true only at longer SOAs. Although we

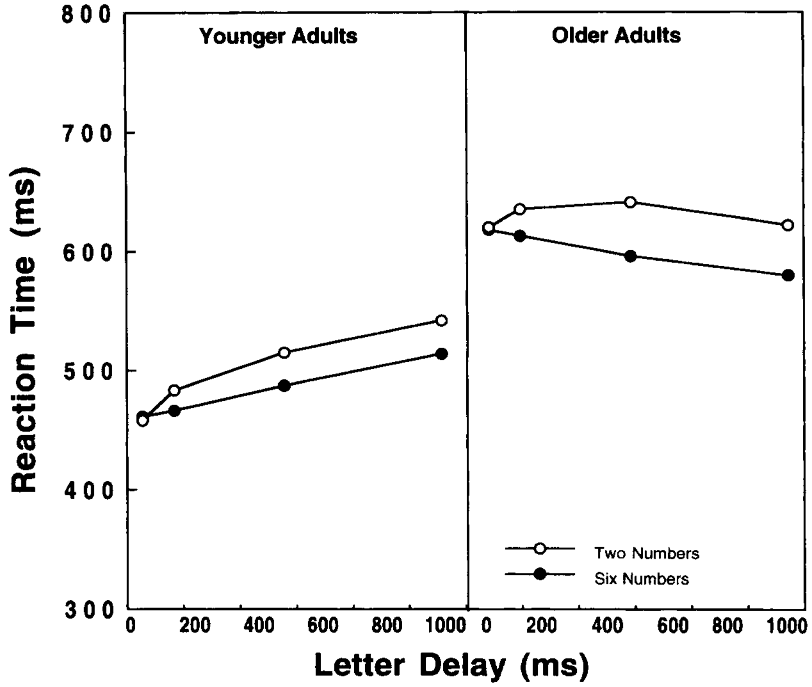

Figure 20. Experiment 5: Mean Task 1 reaction time as a function of age group and letter delay for two-choice and six-choice versions of Task 2.

have no good explanation for this result, it is clearly inconsistent with a capacity shared between the tasks. Once again, there is no support for the capacity-sharing model.

The interesting result was the overadditive interaction of age group and SOA with older adults slowed noticeably more at short SOAs than were younger adults. This result was predicted by both models and had been observed in Experiments 1 and 4, with keypress responses to Task 2, but was eliminated in Experiment 3, in which the response to Task 2 was changed from a keypress to a voice response. Because Experiment 5 also used a voice response to Task 2, a similar result might have been expected. In both experiments, older adults were not significantly slower than younger adults; nevertheless, mean RTs for younger and older adults on the letter-alone task were virtually identical in Experiment 3, whereas in Experiment 5 number-alone RTs were 30 ms slower for older adults. There was some evidence that participants were withholding responses to Task 1 and that older adults were somewhat, but not significantly, more likely to do this. Nonetheless, the likelihood of withholding a response was not affected by the SOA, so once again response grouping cannot account for the interaction of age group and SOA. It appears that the absence of an interaction of age group and SOA in Experiment 3 is the anomalous result, but we have no good explanation why it occurred.

Experiment 6

Still another prediction of the task-switching model is that factors that affect the difficulty of response selection in Task 1 (or of any stage before the switching mechanism) will have an effect on performance in Task 2 that is overadditive with the effects of SOA. When the tasks overlap, increasing the difficulty of response selection in Task 1 extends the time that Task 2 must wait for the response-selection mechanism to become available. If, however, Task 2 is delayed sufficiently that response selection in Task 1 has been completed, the difficulty of that selection will have no effect. Consistent with this prediction, Karlin and Kestenbaum (1968) found an overadditive interaction of the number of Task 1 alternatives with SOA. The prediction of the task-switching model was tested in Experiment 6. In this case, the capacity-sharing model makes precisely the same prediction, because increasing the difficulty of Task 1 reduces the resources available to Task 2. The difficulty of response selection was manipulated by increasing the number of choice alternatives in Task 1 from two to four.

Method

Participants

There were 20 younger and 20 older adults drawn from the same populations as the prior experiments. Their characteristics are given in Table 1.

Design and Procedure

Color-alone tasks. There were two versions of the color-alone task: one with two colors, the other with four colors. 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 (in the two-color version) or to red, green, purple, or dark grey (in the four-color version). The participant was instructed to identify the color as quickly as possible by pressing a key with the left hand. In the two-color version, the participant pressed the *q* key with the middle finger of the left hand for blue or the *w* key with the index finger of the left hand for yellow. In the four-color version, *z* was pressed with the fourth finger for red, *x* was pressed with the third finger for green, *c* was pressed with the middle finger for purple, or *v* was pressed with the index finger for dark grey. Labels that identified the colors were placed just above the appropriate 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 signalled by a tone. There were 120 trials. The first 20 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.

Letter-alone task. Each trial began with presentation of the letter *X* in white centered on the display. After 500 ms, the *X* was replaced by an *A* or *B* 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 by pressing the period key with the index finger of the right hand for *A* or the slash key for *B*. Labels (*A* and *B*) were placed just above the keys. The stimulus remained visible for 7,500 ms or until a response was sensed. Errors were signaled by a tone. There were 120 trials. The first 20 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 task. There were two versions of the dual task: one with two colors, the other with four. 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 (in the two-color version) or to red, green, purple, or dark grey (in the four-color version). The participant was instructed to respond as in the color-alone task. At an SOA of 50, 150, 500, or 1,000 ms after the color changed, the *X* was replaced by an *A* or *B* (the color remained the same). The stimulus was changed back to a white *X* 200 ms after the *A* or *B* had appeared. The participant was instructed to respond to the letter as in the letter-alone task. The time allowed for a response to the color was 1,500 ms; for the letter, time allowed was 5,000 ms. The instructions emphasized responding as quickly as possible to each task. Errors were signaled by tones, a high tone for color errors and a low tone for letter errors. The number of practice trials was controlled by the participant. All participants completed at least one block of 16 practice trials. Then, they could complete as many additional blocks of 16 practice trials as necessary to feel comfortable with the task. One younger adult completed 32 trials and another completed 64; two older adults completed 32 and one completed 64. The practice trials were 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.

Participants first completed the letter-alone task. The order of the two-color and four-color tasks was counterbalanced across participants. Half of the participants completed the two-color-alone task followed by the two-color dual task and then the four-color-alone task followed by the four-color dual task; the other half of the participants completed the four-color tasks and then the two-color tasks.

Results

Color-Alone Tasks

ANOVAs were carried out on the dependent measures from the color-alone tasks with age group as a between-subjects variable and number of colors (2 and 4) as a within-subjects variable. For RT, all effects were significant: For age group, $F(1, 38) = 15.09$, $p < .001$, $MSE = 9{,}454.53$; for number of colors, $F(1, 38) = 492.34$, $p < .001$, $MSE = 1{,}708.44$; for the interaction of age group and number of colors, $F(1, 38) = 23.50$, $p < .001$, $MSE = 1{,}708.44$. Older adults ($M = 633$ ms) were slower than younger adults ($M = 543$ ms); RTs with four possible colors ($M = 697$ ms) were slower than RTs with two possible colors ($M = 479$ ms); and the difference between two and four colors was larger for older adults ($M = 266$ ms) than for younger adults ($M = 170$ ms). For the proportion correct, all effects were again significant: For age group, $F(1, 38) = 6.52$, $p = .015$, $MSE = 0.02$; for number of colors, $F(1, 38) = 15.75$, $p < .001$, $MSE = 0.01$; for the interaction of age group and number of colors, $F(1, 38) = 4.77$, $p = .036$, $MSE = 0.01$. The proportion correct was higher for younger adults ($M = 0.95$) than for older adults ($M = 0.86$); the proportion correct was higher for two choices ($M = 0.94$) than for four choices ($M = 0.87$); and the dropoff in accuracy from two to four choices was greater for older adults ($M = 0.10$) than for younger adults ($M = 0.04$).

Letter-Alone Task

There was no difference between younger ($M = 467$ ms) and older adults ($M = 465$ ms) in the mean voice RT to the letter, $F(1, 38) = 0.01$, *ns*, $MSE = 38.38$. The letter responses were not scored for correctness.

Dual Tasks

Task 2. ANOVAs were carried out on Task 2 measures with age group as a between-subjects variable and number of colors and SOA as within-subjects variables. For RT2, there were significant main effects of number of colors and of SOA: For number of colors, $F(1, 38) = 37.03$, $p < .001$, $MSE = 26{,}268.87$; for SOA, $F(3, 114) = 118.28$, $p < .001$, $MSE = 18{,}820.74$. The mean RT2s are shown in Figure 21. As can be seen in Figure 21, RT2s were longer when Task 1 had four colors than when it had two colors, and, as in the preceding experiments, RT2 increased with decreasing SOA. There were significant interactions of age group and number of colors and number of colors and SOA: For age group and number of colors, $F(1, 38) = 8.73$, $p = .005$, $MSE = 26{,}268.87$; for number of colors and SOA, $F(3, 114) = 54.11$, $p < .001$, $MSE = 4{,}835.91$. Older adults were faster than younger adults with two colors (*M*s = 502 ms and 549 ms, respectively), whereas younger adults were faster than older adults with four colors (*M*s = 608 ms and 670 ms, respectively). Inspection of Figure 21 shows that RT2 increased more with decreasing SOA with four colors in Task 1 than it did with two colors in Task 1. Neither the interaction of age group with SOA nor the three-way interaction of age group, number of colors, and SOA were significant, $Fs < 1$.

For ACC2, there were significant main effects of the number of colors and of SOA: For number of colors, $F(1, 38) = 10.61$, $p = .002$, $MSE = 0.01$; for SOA, $F(3, 114) = 23.48$, $p < .001$, $MSE = 0.01$. Accuracy was lower with two colors ($M = 0.89$) than with four colors ($M = 0.92$), and

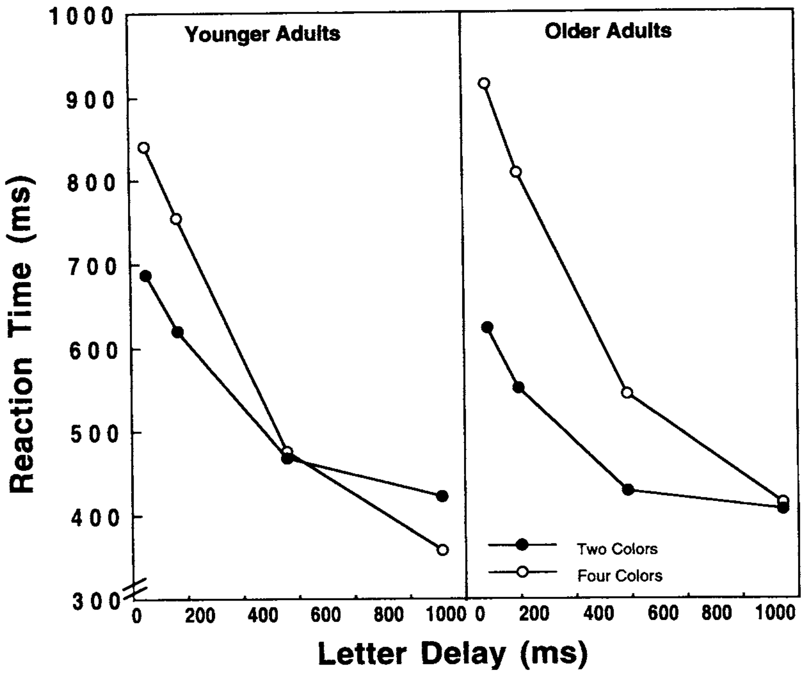

Figure 21. Experiment 6: Mean Task 2 reaction time as a function of age group and letter delay for two-color and four-color versions of Task 1.

accuracy generally declined with increasing SOA, from a mean of 0.94 at 50-ms SOA to a mean of 0.80 at 1,000-ms SOA. The effect of SOA was qualified by a significant interaction of number of colors and SOA, $F(1, 38) = 6.48$, $p < .001$, $MSE < .01$, with the proportion correct slightly lower for four colors than for two colors at 50-ms SOA but higher at longer SOAs.

Task 1. Analysis of RT1s showed significant main effects of age group and number of colors: For age group, $F(1, 38) = 9.54$, $p = .004$, $MSE = 168{,}962.02$; for number of colors, $F(1, 38) = 390.18$, $p < .001$, $MSE = 6{,}547.37$. The means are shown in Figure 22. As can be seen, older adults were slower than younger adults, and RT1s were slower when there were four choices than when there were two choices. There were significant interactions of age group with number of colors and number of colors with SOA: For age group and number of colors, $F(1, 38) = 13.05$, $p = .001$, $MSE = 6{,}547.37$; for number of colors and SOA, $F(3, 114) = 15.67$, $p < .001$, $MSE = 1{,}524.11$. Older adults were slowed more by going from two to four choices ($M = 230$ ms) than were younger adults ($M = 175$ ms). RT1s increased slightly from 50-ms SOA to 1,000-ms SOA with two colors, whereas they remained essentially unchanged with SOA with four colors.

For ACC1, there were significant main effects of the number of colors and of SOA: For number of colors, $F(1, 38) = 9.43$, $p = .004$, $MSE = 0.02$; for SOA, $F(3, 114) = 19.44$, $p < .001$, $MSE < .01$. The proportion correct was higher for two colors ($M = 0.87$) than for four colors ($M = 0.83$) and was lower at the 50-ms SOA ($M = 0.81$) than at longer SOAs ($M = 0.86$ for 150-, 500-, and 1,000-ms SOA). The effect of SOA was qualified by an interaction of number of colors and SOA, $F(3, 114) = 14.37$, $p < .001$, $MSE < .01$. The four-color dual task showed the more pronounced drop at 50-ms SOA.

Analysis of the proportion of timeout errors produced a significant effect of SOA, $F(3, 114) = 4.36$, $p = .034$, $MSE < .01$. Timeout errors were more likely at 1,000-ms SOA ($M = 0.06$) than at 50-, 150-, or 500-ms SOA ($Ms = 0.03$, 0.04, and 0.03, respectively). Analysis of the proportion of long RT1s produced a significant main effect of number of choices and significant interactions of age group and number of colors and of number of colors and SOA: For number of colors, $F(1, 38) = 34.09$, $p < .001$, $MSE = 0.01$; for age group and number of colors, $F(1, 38) = 6.64$, $p = .014$, $MSE = 0.01$; for number of choices and SOA, $F(3, 114) = 3.67$, $p = .026$, $MSE < .01$. Long RT1s were more likely with four colors ($M = 0.12$) than with two colors ($M = 0.05$), and the difference was greater for older adults ($M = 0.10$) than for younger adults ($M = 0.04$). In addition, they were more likely at 1,000-ms SOA ($M = 0.11$) than at shorter SOAs ($M = 0.08$ for all three).

Discussion

Both models predicted that the effects of increasing the difficulty of response selection in Task 1 would have effects on Task 2 RTs that were overadditive with those of SOA. That prediction was confirmed. The capacity-sharing model would also predict an interaction of Task 1 difficulty and SOA in the RTs in Task 1, but that was not found. To the

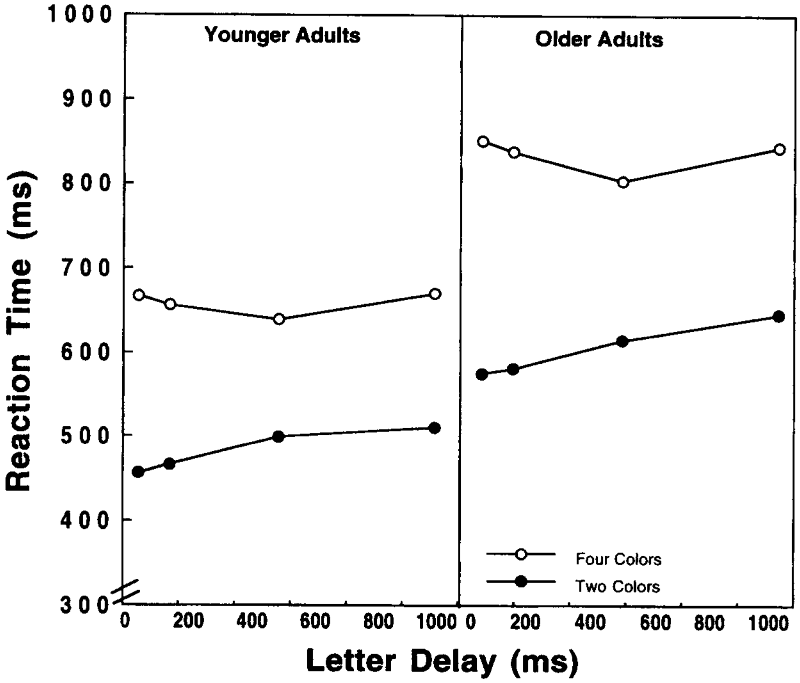

Figure 22. Experiment 6: Mean Task 1 reaction time as a function of age group and letter delay for two-color and four-color versions of Task 1.

extent there was any relation between SOA and RT for Task 1, it was in the wrong direction: There was a slight decrease in RT with decreasing SOA (and that only for the easier version of Task 1).

Long RTs to Task 1 were frequent, particularly for the more complex version of the task and for older adults. It seems likely that these results reflect the difficulty of the task rather than strategic withholding of Task 1 responses. In addition, long RTs and timeout errors were both most frequent at the longest SOA, the condition in which, it has been argued, responses should be least likely to be withheld.

Experiment 7

Pashler (1994a) has suggested that the demands of preparing for two different tasks may result in interference beyond that because of the inability of the response-selection mechanism to handle more than one task at a time. Suppose that the stimulus–response mapping for the second task cannot be put into place at the outset of a trial (or, at least, not put into place fully); it must wait until the mapping for the first task has been used and a response initiated. A more complex Task 2 mapping would serve to lengthen the period the task would have to wait until its mapping was put into place and response selection begun. At long SOAs, the Task 2 mapping would be fully instantiated, and the difficulty of Task 1 would no longer have an effect, but, at short SOAs, the Task 2 mapping would not be instantiated. Further, it would be delayed more by a more complex Task 1 mapping. Figure 23 shows the elaborated version of the task-switching model. In a task with a less complex Task 1 mapping, the mappings for both tasks can be instantiated before the trial begins. A more complex mapping in Task 1 not only pushes back the point at which the response-selection mechanism is switched to Task 2 but also prevents instantiation of the Task 2 mapping. The mapping cannot be instantiated until the response-selection mechanism is freed by Task 1. At short SOAs, this will mean that the Task 2 mapping will be instantiated after the switch but before response selection in Task 2 begins. The time to instantiate the mapping will be added to Task 2 RT. With a long SOA, however, the Task 2 mapping can be instantiated after the response-selection mechanism is freed by Task 1 and before the Task 2 stimulus arrives. In this case, the time to instantiate the Task 2 mapping has no effect on the Task 2 RT. Consequently, the effects of increasing the complexity of the Task 2 mapping should be overadditive with the effects of SOA. Notice that the effects of increasing the complexity of the Task 1 mapping add to the RTs in Task 1 but that they are in no way affected by the SOA. The mapping for Task 1 is assumed to be in place before the trial starts and is unaffected by the overlap between the tasks; the overlap affects only the second unprepared or less well-prepared task. Notice also that the effects of manipulating the complexity of the response mapping in Task 2 are not the same as the effects of manipulating the difficulty of response selection. Increasing the complexity of the Task 2 mapping should have effects that are overadditive with those of SOA, whereas increasing the difficulty of response selection in Task 2 should contribute additively to the effects of SOA, as was observed in Experiment 5. Pashler (1994b) argued that,

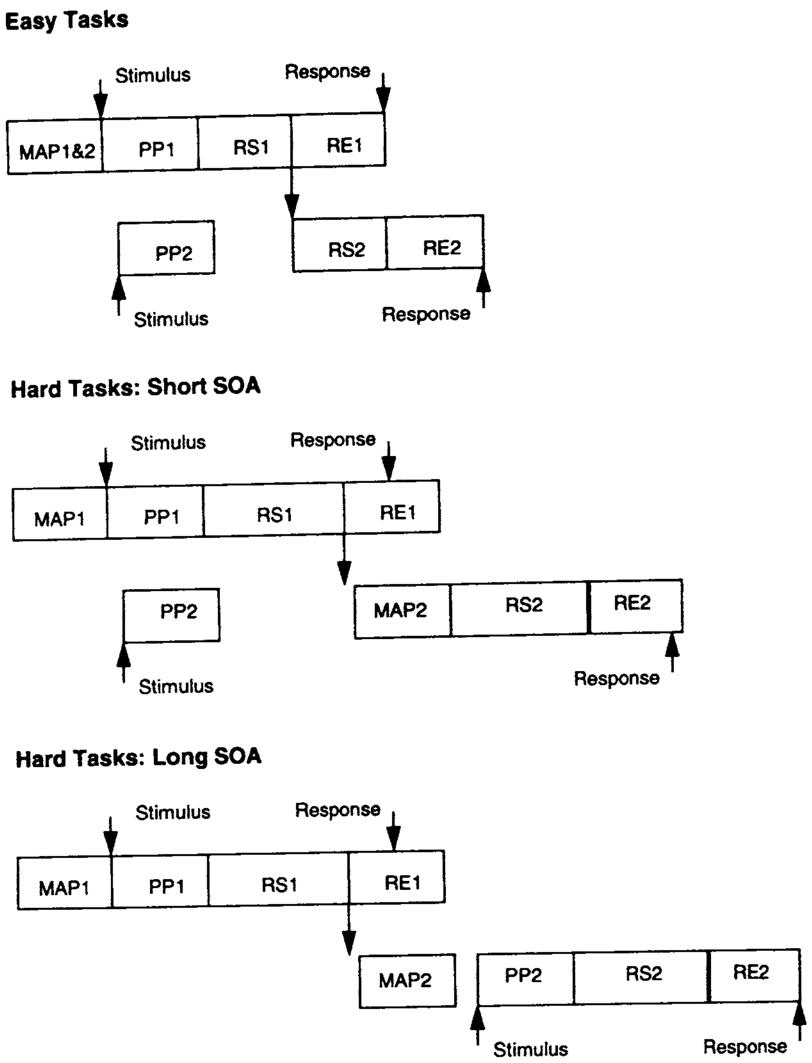

Figure 23. Task-switching model elaborated to include stages in which the response mapping for each task is instantiated. PP = perceptual processing; RS = response selection; RE = response execution; MAP = instantiation of stimulus-response mapping; SOA = stimulus onset asynchrony. (Top) With relatively easy tasks, mappings for both Task 1 and Task 2 can be instantiated before the trial starts. (Middle) With hard tasks at short delays, execution of Task 2 must be delayed until the mapping can be instantiated. (Bottom) With hard tasks at long delays, the mapping for Task 2 can be instantiated before the stimulus appears, and execution is not delayed.

in most cases, the mappings for both tasks can be prepared fully in advance; activating a new mapping and suppressing a completed mapping (which he termed *task switching*) are necessary only when the two successive tasks map the same stimuli onto different responses. In the present experiment, changing the aspect of the stimulus that is attended from its color to its shape may necessitate task switching.

Experiment 7 explored the effects on dual-task interference of manipulating the response mappings in both Task 1 and Task 2. The stimuli were those used in Experiment 1: The stimulus first changed from a white *X* to a red or green *X*, and the task was to identify the color; it next changed from an *X* to an *A* or *B*, and the task was to identify the letter. The complexity of the stimulus–response mappings was manipulated by using both a two-choice (or hard) and a go/no-go (or easy) version of each task. For example, for the color task, the hard version required one response for red and a different response for green. In the easy version, a response would be required for one color, but no response was to be given for the other color. Notice that the decision required is the same in both versions of the task: The color must be identified and a decision made on the basis of that identification. In the hard task, that decision leads to the initiation of one of two possible overt motor responses. In the easy task, there is no uncertainty about the overt response; the decision either leads to the release of that response or it does not. The elaborated version of the task-switching model predicts that increasing the complexity of either the response mapping for Task 1 or for Task 2 will interact overadditively with SOA in Task 2 RTs: The additional slowing will increase as the SOA is shortened.

Task combinations with the easy version of Task 1 allow a further exploration of the effects on Task 2 of executing a Task 1 response. On some trials, an overt response will be required for Task 1, whereas on others it will not. The response mapping for those two types of trials is exactly the same; the only difference is whether a motor response is organized and executed. Task 2 performance on these two types of trials can be compared to determine whether response execution contributes to the dual-task interference.

Keypress responses were used for both tasks in Experiment 7 to create a high functional similarity between the response requirements of the two tasks. Experiment 5 required newly learned keypress responses to Task 1 but well-learned voice responses to Task 2. Requiring newly and equally well-learned responses to both tasks provides an equal opportunity for interference by either task.

Method

Participants

The participants were 20 younger adults and 20 older adults from the same populations as the preceding experiments. Their characteristics are given in Table 1.

Color-Alone Task

The color-alone task was administered first and was identical to that in Experiment 1, with 25 practice trials and 100 experimental trials. This was the two-choice version of the color task; the go/no-go version was not administered as a color-alone task.

Letter-Alone Task

The letter-alone task was administered second and was also identical to that in Experiment 1, with 25 practice trials and 100 experimental trials. As with the color-alone task, this was the two-choice version of the letter task; the go/no-go version was not administered as a letter-alone task.

Dual Tasks

For convenience, we call the two-choice version of each task the hard version and the go/no-go version the easy version. The hard–hard dual task was the third task completed. It was identical to the dual task in Experiment 1, except that there were twice as many practice trials, 32 rather than 16. As before, there were 192 experimental trials. There were 48 experimental trials at each of the four SOAs, 50, 150, 500, and 1,000 ms.

In the hard–easy version of the dual task, a response was required for both colors but for only one of the letters. The participant was instructed to respond to the color by pressing the *z* key for red or the *x* key for green. However, for the letter, the participant responded only to *A*, pressing the period key. The participant was instructed not to respond to the letter if it was *B*; rather, he or she should simply let the letter go by. The trials were structured as in the hard–hard task.

In the easy–hard version of the dual task, a response was required for only one of the colors but for both of the letters. The participant responded to red by pressing the *z* key but gave no response to green. For the letters, the participant responded to *A* by pressing the period key and to *B* by pressing the slash key. The trials were structured as in the hard–hard task.

In the easy–easy version of the dual task, a response was required for one color and for one letter. The participant responded to red by pressing the *z* key but gave no response to green and responded to *A* by pressing the period key but gave no response to *B*. The trials were structured as in the hard–hard task.

The order of the last three tasks—the hard–easy, easy–hard, and easy–easy versions of the dual task—was counterbalanced across participants.

Results

Color-Alone Task

Although the age difference in RT was not significant ($M = 496$ ms for younger adults and $M = 539$ ms for older adults), $F(1, 38) = 3.52, p = .07, MSE = 5{,}048.95$, younger adults did have a higher proportion correct ($M = 0.98$) than older adults ($M = 0.95$), $F(1, 38) = 5.81, p = .02, MSE = 0.01$.

Letter-Alone Task

On the letter-alone task, older adults were both slower ($M = 478$ ms) and less accurate ($M = 0.97$) than younger adults (Ms = 429 ms and 0.99, respectively): For RT, $F(1, 38) = 5.70$, $p = .02$, $MSE = 4{,}087.73$; for proportion correct, $F(1, 38) = 5.54, p = .02, MSE < .01$.

Dual Tasks

Task 2. An ANOVA was carried out on the RT2s and ACC2s with age group as a between-subjects variable and first-task complexity (hard and easy response mapping), second-task complexity (hard and easy response mapping), and SOA (50, 150, 500, and 1,000 ms) as within-subjects variables. Mean RT2s are shown in Figure 24. The analysis of RT2s showed significant main effects of age group, of first-task complexity, of second-task complexity, and of SOA: For age group, $F(1, 38) = 13.41, p < .001, MSE = 342{,}103.58$; for first-task complexity, $F(1, 38) = 76.25, p < .001$, $MSE = 21{,}413.24$; for second-task complexity, $F(1, 38) = 24.06$, $p < .001$, $MSE = 37{,}246.45$; for SOA, $F(3, 114) = 437.56$, $p < .001$, $MSE = 11{,}560.45$. Older adults ($M = 828$ ms) were slower than younger adults ($M = 718$ ms); RT2s in the easy first task ($M = 720$ ms) were faster than those in the hard first task ($M = 826$ ms); RT2s in the easy second task ($M = 737$ ms) were faster than RT2s in the hard second task ($M = 809$ ms); and mean RT2s increased from 577 ms at 1,000-ms SOA to 976 ms at 50-ms SOA. There were also significant interactions of age group and SOA, of first-task complexity and SOA, and of second-task complexity and SOA: For age group and SOA, $F(3, 114) = 4.86$, $p = .017$, $MSE = 11{,}560.45$; for first-task complexity and SOA, $F(3, 114) = 148.90, p < .001, MSE = 3{,}258.05$; for second-task complexity and SOA, $F(3, 114) = 5.93, p =$

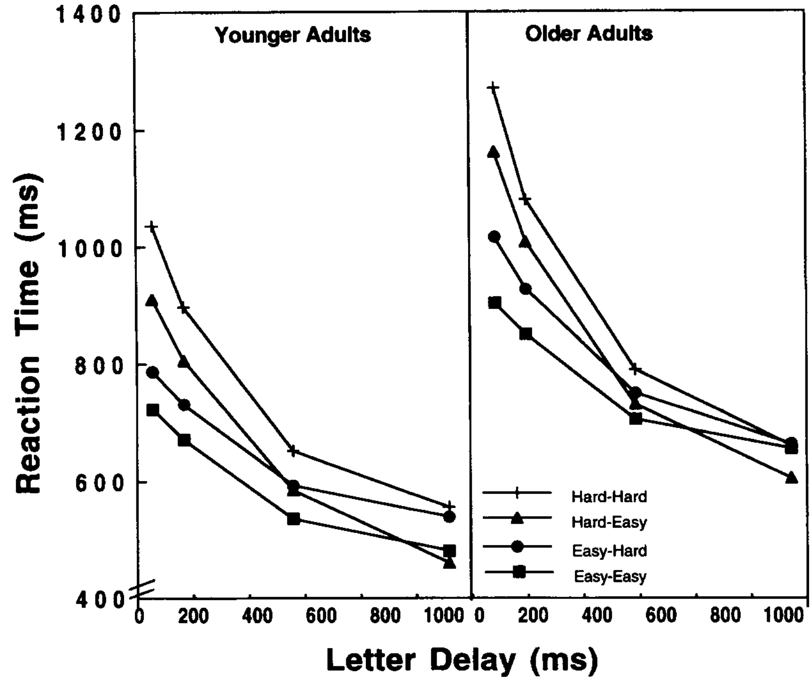

Figure 24. Experiment 7: Task 2 reaction times as a function of age group, letter delay, Task 1 complexity (easy or hard), and Task 2 complexity (easy or hard).

.001, *MSE* = 3,229.64. All three interactions were overadditive. For age group and SOA, older adults were 14 ms faster on average than younger adults at 1,000-ms SOA, whereas younger adults were 224 ms faster than older adults at 50-ms SOA. For first-task complexity and SOA, the hard version was 14 ms faster on average than the easy version at 1,000-ms SOA, whereas the easy version was 237 ms faster at 50-ms SOA. The interaction of second-task complexity and SOA was weaker than the interaction of first-task complexity and SOA, with the mean difference between the hard and easy versions of the second task increasing from 54 ms at 1,000-ms SOA to 104 ms at 50-ms SOA. The three-way interaction of first-task complexity, second-task complexity, and SOA was not significant, $F(3, 114) = 0.79$, *ns*, *MSE* = 3,162.21. The three-way interaction of age group, first-task complexity, and SOA approached significance, $F(3, 114) = 2.89$, $p = .060$, *MSE* = 3,258.05. The effect was significant by a conventional test ($p = .039$). For younger adults, the harder version was 149 ms slower than the easy version at 1,000-ms SOA and 218 ms slower at 50-ms SOA, whereas, for older adults, the hard version was 124 ms slower than the easy version at 1,000-ms SOA and 256 ms slower at 50-ms SOA.

The analysis of ACC2s showed significant main effects of age group, of first-task complexity, and of second-task complexity: For age group, $F(1, 38) = 3.96$, $p = .050$, *MSE* = 0.13; for first-task complexity, $F(1, 38) = 19.35$, $p < .001$, *MSE* = 0.05; for second-task complexity, $F(1, 38) = 5.95$, $p = .02$, *MSE* = 0.01. There were significant interactions of first- and second-task complexity, of second-task complexity with SOA, and of first- and second-task complexity with SOA: For first- and second-task complexity, $F(1, 38) = 8.73$, $p = .005$, *MSE* = 0.02; for second-task complexity and SOA, $F(3, 114) = 3.15$, $p = .028$, *MSE* < .01; for first- and second-task complexity and SOA, $F(3, 114) = 4.39$, $p = .006$, *MSE* < .01. The mean ACC2s are shown in Table 4.

Go versus no-go trials. An analysis was carried out on the RT2s from the easy–easy and easy–hard dual tasks. Means were obtained separately for trials on which a color response was required (go trials) and those on which no color response was required (no-go trials). Age group was a between-subjects variable, and the within-subjects variables were second-task complexity (easy and hard), SOA, and trial type (go and no-go). The significant effects involving the trial type factor were a main effect of trial type, $F(1, 38) = 20.76$, $p < .001$, *MSE* = 10,202.10, and interactions of age group and trial type, $F(1, 38) = 4.56$, $p = .040$, *MSE* = 10,202.10, and of trial type and SOA, $F(3, 114) = 46.87$, $p < .001$, *MSE* = 5,493.81. The interaction of age group with trial type and SOA was not significant, $F(3, 114) = 2.15$, $p = .098$, *MSE* = 5,493.81. The mean RT2s are shown in Figure 25. Go trials resulted in longer RT2s ($M = 714$ ms) than no-go trials ($M = 673$ ms). The difference between go and no-go trials was greater for older adults ($M = 53$ ms) than for younger adults ($M = 29$ ms). As can be seen in Figure 25, the interaction of trial type and SOA was overadditive, with the difference between go and no-go trials decreasing as the SOA lengthened.

Task 1. Mean RT1s are shown in Figure 26. Analysis of RT1s showed significant main effects of first-task complexity, of second-task complexity, and of SOA: For first-task

Table 4
Proportion Correct for Task 2 in Experiment 7

	Task 1: Easy				Task 1: Hard			
	Task 2: Easy		Task 2: Hard		Task 2: Easy		Task 2: Hard	
SOA (ms)	Younger	Older	Younger	Older	Younger	Older	Younger	Older
50								
M	.97	.93	.98	.92	.96	.80	.92	.81
SD	.11	.12	.03	.11	.05	.18	.06	.18
100								
M	.96	.92	.98	.95	.96	.88	.93	.81
SD	.11	.11	.03	.07	.05	.14	.05	.20
500								
M	.97	.93	.98	.92	.96	.87	.89	.80
SD	.11	.08	.03	.11	.06	.19	.09	.20
1,000								
M	.96	.93	.98	.94	.88	.88	.79	.82
SD	.11	.09	.02	.07	.21	.20	.28	.18

Note. SOA = stimulus onset asynchrony.

complexity, $F(1, 38) = 14.23, p < .001, MSE = 34{,}319.12$; for second-task complexity, $F(1, 38) = 13.16, p < .001, MSE = 14{,}362.92$; for SOA, $F(3, 114) = 3.43, p = .020, MSE = 24{,}619.58$. There were significant interactions of age group and SOA, of first-task complexity and SOA, of second-task complexity and SOA, and of first- and second-task complexity and SOA: For age group and SOA, $F(3, 114) = 5.75, p = .001, MSE = 24{,}619.58$; for first-task complexity and SOA, $F(3, 114) = 8.66, p < .001, MSE = 4{,}260.82$; for second-task complexity and SOA, $F(3, 114) = 9.48, p < .001, MSE = 3{,}764.88$; for first- and second-task complexity and SOA, $F(3, 114) = 4.42, p = .006, MSE = 3{,}845.79$. From inspection of Figure 26, it is clear that many of the interactions are due to differences between the easy–hard task and the remaining tasks. Consequently, a second analysis was carried out omitting the data from the easy–hard condition: Age group was a between-subjects variable, and task (hard–hard, hard–easy, and easy–easy) and SOA were within-subjects variables. This analysis produced a main effect of task and of SOA: For task, $F(2,$

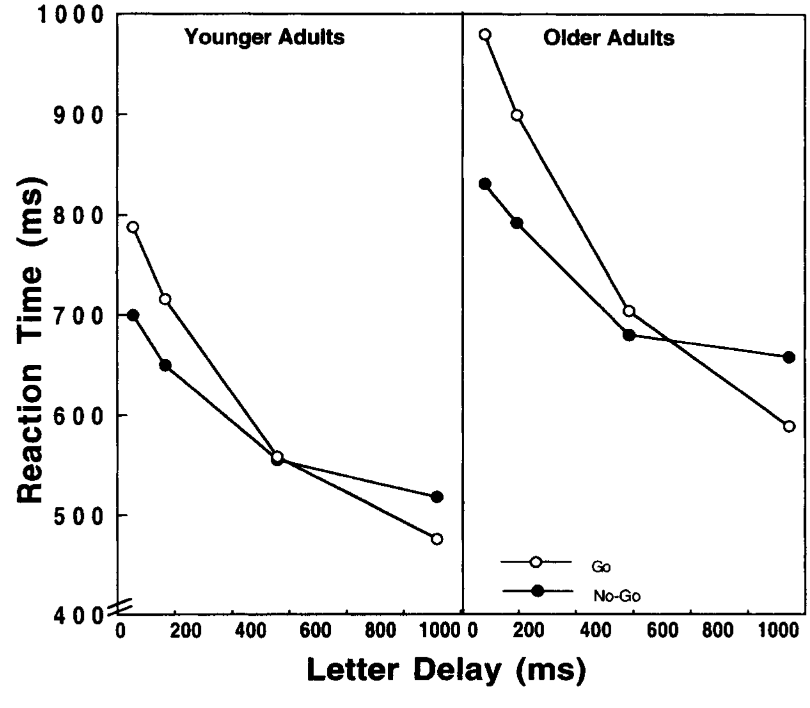

Figure 25. Experiment 7: Task 2 reaction times as a function of age group and letter delay for trials on which a response was required in Task 1 (go trials) or was not required (no-go trials).

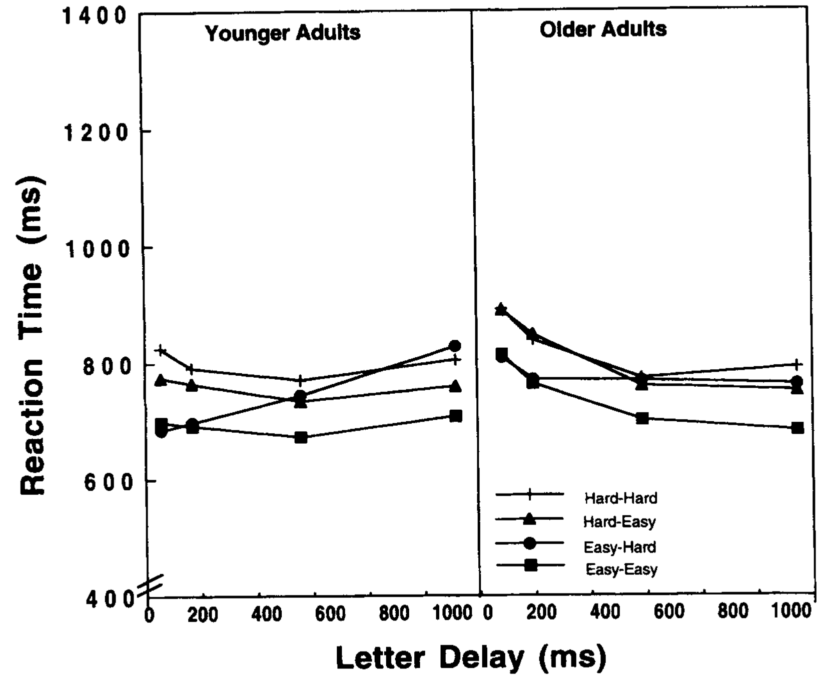

Figure 26. Experiment 7: Task 1 reaction times as a function of age group, letter delay, Task 1 complexity (easy or hard), and Task 2 complexity (easy or hard).

76) = 15.43, $p < .001$, $MSE = 23{,}054.36$; for SOA, $F(3, 114) = 8.13$, $p < .001$, $MSE = 17{,}482.51$. The RT1s in the hard–hard task ($M = 803$ ms) were longer than those in the hard–easy task ($M = 776$ ms), which were, in turn, longer than those in the easy–easy task ($M = 706$ ms). The main effect of SOA was qualified by an interaction of age group and SOA, $F(3, 114) = 8.13$, $p = .019$, $MSE = 17{,}482.51$. For younger adults, RT1s dropped moderately from 50-ms SOA ($M = 758$ ms) to 500-ms SOA ($M = 715$ ms) then increased (for 1,000-ms SOA, $M = 756$ ms); for older adults, RT1s dropped sharply from 50-ms SOA ($M = 855$ ms) to 500-ms SOA ($M = 733$ ms), then leveled (for 1,000-ms SOA, $M = 730$ ms).

Analysis of ACC1s showed a significant main effect of first-task complexity, $F(1, 38) = 6.09$, $p = .019$, $MSE = 0.02$. The proportion correct was lower in the hard version ($M = 0.88$) than in the easy version ($M = 0.91$). There were significant interactions of age group and SOA and of second-task complexity and SOA: For age group and SOA, $F(3, 114) = 8.30$, $p = .005$, $MSE = 0.02$; for second-task complexity and SOA, $F(3, 114) = 5.66$, $p = .005$, $MSE < .01$. For the younger group, accuracy remained stable from 50- to 500-ms SOA ($Ms = 0.94$) and then dropped (for 1,000-ms SOA, $M = 0.85$), whereas for older adults, accuracy increased monotonically from 50-ms SOA ($M = 0.83$) to 1,000-ms SOA ($M = 0.90$). For Task 2 complexity and SOA, accuracy was slightly higher in the hard version than the easy version at 50- and 150-ms SOA ($Ms = 0.89$ vs. 0.88 and 0.92 vs. 0.91, respectively), but accuracy was higher in the easy version at 500- and 1,000-ms SOA ($Ms = 0.93$ vs. 0.91 and 0.89 vs. 0.86, respectively).

An ANOVA on the proportion of timeout errors produced a significant interaction of age group and SOA, $F(3, 114) = 6.60$, $p = .004$, $MSE = 0.01$. The mean proportions are shown in Table 5. For younger adults but not older adults, timeout errors increased with increasing SOA. Analysis of long RTs produced significant main effects of Task 1 complexity, Task 2 complexity, and SOA: Respectively, $F(1, 38) = 63.72$, $p < .001$, $MSE = 0.04$; $F(1, 38) = 5.08$, $p = .031$, $MSE = 0.01$; and $F(3, 114) = 7.35$, $p < .001$, $MSE = 0.01$. There were significant interactions of Task 1 complexity and SOA, Task 2 complexity and SOA, and of both tasks and SOA: Respectively, $F(3, 114) = 8.17$, $p < .001$, $MSE = 0.01$; $F(3, 114) = 2.81$, $p = .043$, $MSE < .01$; and $F(3, 114) = 4.39$, $p = .006$, $MSE < .01$. There were also significant interactions of age group with SOA, with Task 1 and Task 2 complexity, and with both tasks and SOA: Respectively, $F(3, 114) = 4.75$, $p = .004$, $MSE = 0.01$; $F(3, 114) = 4.49$, $p = .041$, $MSE = 0.01$; and $F(3, 114) = 3.52$, $p = .018$, $MSE < .01$. The mean proportions of long RTs are shown in Table 6. Inspection of Table 6 shows that the hard versions of the tasks produced more long RT1s than the easier versions, and this was more true for Task 1. When both tasks were easy, the proportion of long RT1 increased with decreasing SOAs in both age groups. With the easy version of Task 2, the proportion also increased with decreasing SOA for older adults, particularly with the hard version of Task 1, but not for younger adults. With the easy version of Task 1 and the hard version of Task 2, the proportion decreased as SOA decreased for younger adults but increased slightly for older adults.

Table 5
Proportion Timeout Errors for Task 1 in Experiment 7

	Task 1: Easy				Task 1: Hard			
	Task 2: Easy		Task 2: Hard		Task 2: Easy		Task 2: Hard	
SOA (ms)	Younger	Older	Younger	Older	Younger	Older	Younger	Older
50								
M	.10	.22	.05	.11	.04	.09	.04	.19
SD	.22	.20	.08	.15	.05	.09	.04	.24
100								
M	.06	.14	.04	.10	.04	.11	.05	.19
SD	.13	.15	.07	.10	.05	.16	.04	.27
500								
M	.07	.11	.06	.09	.09	.09	.07	.17
SD	.15	.14	.07	.12	.15	.12	.07	.24
1,000								
M	.11	.11	.13	.09	.08	.11	.18	.14
SD	.19	.15	.23	.13	.20	.11	.28	.22

Note. SOA = stimulus onset asynchrony.

Discussion

Task 2

There was a strongly overadditive interaction of Task 1 complexity and SOA on RTs in Task 2, confirming the results of Experiment 6. The hard version of Task 1 slowed Task 2 significantly when the tasks overlapped but had little or no effect when the two tasks were well separated. Considering only the easy versions of Task 1, there was also an overadditive interaction of SOA and whether or not Task 1 required a response. Trials on which a Task 1 response was required produced longer Task 2 RTs than trials with no response when the two tasks overlapped, but the difference vanished when the two tasks were well separated. In this case, the response mapping in Task 1 is exactly the same on both types of trials. The only difference is whether it was necessary to organize and execute a response. So, not only does a more complex response mapping in Task 1 result in more interference with Task 2, but also a response selection that requires an overt response results in greater interference than a response selection that does not. At least some aspects of preparation for the physical response must precede the switch.

In addition to the strongly overadditive interactions of Task 1 complexity and of go versus no-go trials with SOA, there was also an overadditive interaction of Task 2 complexity and SOA. This indicates that it takes longer to instantiate a more complex response mapping. The simple task-switching model predicted that the effects of increasing the difficulty of nonperceptual components of Task 2 would be additive with the effects of SOA. The overadditive effects are consistent with the added stage in the extended model in which the response mapping for Task 2 must be instantiated after the selection mechanism becomes available.

Concerning age differences, the interaction of age group and SOA that was found in Experiments 1, 4, and 5 was also

Table 6
Proportion Long RTs (1,000 ≤ RT ≤ 1,500 ms) for Task 1 in Experiment 7

	Task 1: Easy				Task 1: Hard			
	Task 2: Easy		Task 2: Hard		Task 2: Easy		Task 2: Hard	
SOA (ms)	Younger	Older	Younger	Older	Younger	Older	Younger	Older
50								
M	.07	.11	.05	.11	.17	.29	.24	.27
SD	.05	.07	.05	.07	.12	.13	.15	.17
100								
M	.06	.09	.05	.10	.17	.25	.21	.19
SD	.06	.07	.05	.10	.14	.13	.16	.14
500								
M	.06	.05	.09	.08	.19	.15	.19	.14
SD	.06	.05	.10	.09	.21	.13	.20	.12
1,000								
M	.05	.03	.11	.08	.14	.14	.18	.17
SD	.07	.04	.10	.05	.14	.13	.18	.14

Note. RT = reaction time; SOA = stimulus onset asynchrony.

found here: Age differences were greatest at the shortest SOAs. One explanation for this result in some of the experiments was a greater tendency for older adults to withhold their Task 1 responses or to group the two responses, particularly at short SOAs. In this experiment, however, there was little evidence that responses were being strategically withheld. The interactions in the Task 2 RTs of age group, first-task complexity, and SOA and of age group, type of trial (go vs. no-go) and SOA both approached significance. Given the low power of this design to detect as significant a higher order interaction involving a between-subjects variable, these effects may be small but reliable. It is possible that older adults experience greater difficulty in preparing for a new task, which requires motor programs that are highly functionally similar to those in an earlier task which is still under way. Consistent with this interpretation, there was no hint of such an interaction in Experiment 6, in which the responses were in different modalities.

Task 1

Here the most salient findings are the anomalous results for the easy–hard dual task. The functional relationship between Task 1 RT and SOA in this task is quite different from those in the other dual-task conditions, which are quite similar to one another. We have no good explanation for this anomaly. Concentrating on the other versions of the dual task, Task 1 RTs were affected by the SOA, contrary to the predictions of the task-switching model. RTs dropped as the SOA lengthened from 50 to 500 ms (more so for older adults), and then they leveled off or increased. This result was also contrary to the capacity-sharing model because the effects of increasing task difficulty do not potentiate those of SOA as the model predicted they should, but, rather, were additive. Age group, too, had an effect that is additive with those of complexity and SOA, again contrary to the capacity-sharing model. The most likely explanation for these results is postponement of Task 1 responses or grouping of Task 1 and Task 2 responses by some individuals on some trials.

General Discussion

Across the seven experiments, the predictions of the task-switching model were generally supported. The model predicted correctly that dual-task interference would increase as the SOA between the tasks was decreased. It also predicted correctly that the interference would be eliminated when competition for the response-selection mechanism was removed by suspending the requirement that the Task 2 response be speeded (Experiments 2 and 3). In addition, the dependency between Task 2 RT and Task 1 RT at the level of individual trials was correctly predicted: When Task 2 was speeded, trials with relatively long RT1 also had slow RT2 when the SOA was short, but not when it was long. The most telling confirmation was for the prediction of a subadditive interaction in Experiment 4: The effect of increasing the perceptual difficulty of Task 2 would be least at short SOAs when the interference between the two tasks was greatest. Finally, the task-switching model correctly predicted the finding in Experiment 5 that increasing the difficulty of response selection in Task 2 would have the same effect at all SOAs.

A persistent difficulty for the task-switching model was the finding that SOA affected Task 1 performance. In the model, Task 1 gains first access to the response-selection mechanism. Task 2 is affected by the SOA because that governs how soon after the Task 2 stimulus arrives the mechanism becomes free, but Task 1 should be unaffected by whether Task 2 is waiting or not. It was argued that the effect of SOA on Task 1 performance could have been due to a tendency by some individuals on some trials to withhold their Task 1 response until Task 2 processing was nearly complete. Although the participants were cautioned not to withhold their Task 1 responses, but, rather, to make them as quickly as possible, they were only monitored closely during the practice trials, and the evidence is consistent with the possibility that some resorted to grouping. Withholding the response may have been a way to deal with the difficulty of instantiating and executing two different motor programs that were highly similar. When the two responses were in different modalities in Experiment 3 (simultaneous condition), Experiment 5, and Experiment 6, Task 1 RTs were generally independent of SOA, although this was not true in Experiment 4. The present results are at odds with the absence of such effects in a number of studies in which small numbers of participants are used and extensive efforts are made to assure they do not withhold responses (e.g., McCann & Johnston, 1992; Osman & Moore, 1993; Pashler & O'Brien, 1993). In each of these studies, however, the stimulus for Task 1 was presented aurally, whereas the stimulus for Task 2 was presented visually. In the present experiments, stimuli for both tasks were presented visually. Thus, the increases in Task 1 RTs at short SOAs in the present experiments may reflect specific interference because of a shared input modality. This interference would be in addition to the shared capacity for perceptual processing in the two tasks demonstrated in Experiment 4. Experiment 4 showed that increased perceptual processing difficulty in Task 2 could be absorbed in the time when Task 2 awaited the freeing of the response-selection mechanism, evidenced by the subadditive interaction of Task 2 difficulty and SOA. If capacity for perceptual processing were shared, this would have been an overadditive interaction.

The basic task-switching model assumes that increasing Task 1 difficulty will delay the freeing of the response-selection mechanism and shifting to Task 2. Increasing Task 2 difficulty has its effects only after the response-selection mechanism has been shifted, so it simply delays the Task 2 response. This delay would be the same at all SOAs, so the model predicts that the effects of Task 2 difficulty will be additive with those of SOA. The results require a modification of the model. There must be a stage of Task 2 preparation, when the response mapping for that task is instantiated, that only takes place after the response-selection mechanism is freed by Task 1 and that must be completed before response selection in Task 2 can proceed. If the stimulus for Task 2 arrives before the mapping is in place, response selection must wait until it is. If there is a delay before the stimulus for Task 2 arrives, as there is with a long SOA, the mapping will already be in place, and response selection can begin immediately. The complexity of the Task 2 response mapping should affect RTs in Task 2 at short SOAs but not at long SOAs. The results of Experiment 7 were consistent with the interpretation that the more difficult the Task 2 mapping, the longer it will take to complete the instantiation of that mapping. Moreover, the comparison of Task 2 RTs on trials requiring and not requiring a Task 1 response indicated that, independent of the complexity of the mapping, the necessity of generating a motor response is sufficient to interfere with putting the Task 2 mapping in place. Once again, this interference could also be thought of as a peripheral capacity sharing. The evidence and discussion here has been concerned with Task 2 preparation. It is reasonable to assume that there is a similar stage for Task 1 preparation. That stage would precede the start of the trial, and the manipulations here would not affect it. It could be investigated by manipulating the interval between trials or by changing the response mapping from trial to trial.

Pashler (1994a, 1994b) has also argued that task preparation plays an important role and that dual-task interference may be affected by the demands of preparing and switching between two different mappings. He suggested that the mappings for both tasks can be prepared in advance except when they are highly confusible. Not only are the present results consistent with these assertions, but they also allow us to specify more precisely where in the processing sequence task preparation occurs and what factors affect it.

Task Switching and Response-Selection Bottlenecks

Meyer et al. (1995) have argued that task-switching models incorporating a single, immutable response-selection bottleneck provide a less satisfactory account of multiple-task performance than a model incorporating flexible executive control. In this model, bottlenecks may be placed at a number of points in the processing sequence. Whether and where the bottlenecks are placed is under strategic control. De Jong (1993) reported results consistent with the presence of two bottlenecks: one at response selection, the other at response initiation. As Pashler (1998) has 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. In sum, nothing in the present results contradicts the flexible executive control model, but neither do they 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.

Implications for Aging and Dual-Task Interference

The prevailing theoretical explanation for age differences in performance is that older adults have suffered a reduction in some general cognitive resource. Age differences are expected to be particularly noticeable when the diminished resource must be divided between two tasks to be executed at the same time. This explanation was formalized here as the capacity-sharing model, with a reduced capacity in older adults. The reduced-capacity model predicted that older adults would be slower than younger adults to respond to Task 2 (or less correct when the primary dependent variable was accuracy, as in Experiment 2 and the sequential dual-task condition of Experiment 3) and that the age difference would increase as the overlap between the two tasks increased, that is, as the SOA decreased. Older adults were significantly slower than younger adults in Experiments 1, 4, and 7. In Experiments 3, 5, and 6, however, there was no age difference. Similarly, the predicted overadditive interaction of age group and SOA was observed in Experiments 1, 4, 5, and 7, but was absent in Experiments 2, 3, and 6. In each case in which the interaction was absent, either there was no pressure to respond quickly to Task 2, or the responses to the two tasks were in different modalities (keypress response to Task 1 and voice response to Task 2). These results are inconsistent with the general reduced-resource model. Changes in the motor responses could have an effect in such a model, but they could not eliminate the greater dual-task interference in older adults caused by dividing reduced central resources between the two tasks. By contrast, the results are consistent with a more restricted resource model in which there is a limited capacity for organizing and executing motor responses (cf. Navon & Miller, 1987), a capacity that may be lower in older adults. Naming a letter is a highly overlearned response, whereas giving a newly learned keypress response to a letter is not. Generating two similar keypress responses close together should tax this motor output capacity more than generating a keypress and a voice response.

The capacity-sharing model predicted that any factor that increased the difficulty of either task would result in increased dual-task interference for both tasks. That is, a difficulty manipulation should have its greatest effect with minimal SOA between the tasks, decreasing as the SOA is increased. The reduced-capacity version of the model predicted further that these interactions would be larger in older adults than in younger adults: The effects of the manipulation would be exaggerated at short SOAs in older adults because the capacity to respond to the increased demands would have been diminished. Difficulty was manipulated in four experiments. In Experiment 4, the discriminability of the Task 2 stimuli (letters) was decreased. In Experiment 5, the number of Task 2 alternatives (numbers) was increased. In Experiment 6, the number of Task 1 alternatives (colors) was increased. In Experiment 7, the complexity of the response mapping in either or both of the tasks was increased. The manipulations increased RTs overall, indicating that they were effective, but only when the complexity of Task 1 was varied was there an overadditive interaction of the manipulation with SOA. In no case was there a three-way interaction in which the overadditivity was greater for older than for younger adults. In summary, the reduced-capacity model generally failed to account for the results.

The task-switching model in which a single response-selection mechanism can process only one task at a time was much more successful at accounting for the results. To account for age differences, the additional assumption was made that older adults are simply slower than younger adults. As noted, the model accounted for an increase in dual-task interference with decreasing SOA, and it explained the overadditive interaction of age group and SOA, and the greater age differences at short SOAs. The interaction was present in every task that required speeded keypress responses to both tasks. It was, however, absent in two of the three experiments with voice responses to Task 2. It was argued previously that the interaction could be explained by a greater tendency in older adults to withhold the Task 1 response, particularly in experiments that required a keypress response for both tasks. However, the overadditive interaction of age group and SOA was found in Experiment 4, even though there was no evidence of selective withholding of Task 1 responses, reducing the viability of this explanation. The salient characteristic of the experiments with no interaction of age group and SOA was that the mean RTs for younger and older individuals for Task 2 done alone were virtually identical; thus, the absence of the interaction is probably not theoretically important. The task-switching model also successfully predicted that interference would be removed in both age groups by eliminating the time pressure for the response in Task 1. The model cannot explain the age differences in accuracy that remained when the time pressure was removed, at least without additional ad hoc assumptions.

The task-switching model assumed the presence of response slowing in older adults. It has been suggested that speed of processing may constitute a resource that is diminished in old age (cf. Salthouse, 1988a, 1988b, 1991). It is clear from the results that speed can only be thought of as a capacity-limited resource for the response-selection stage. The observed patterns of slowing in stages preceding and following response selection were not consistent with the interpretation that speed of processing is a general resource.

The basic task-switching model was elaborated to incorporate a task-preparation stage in which response mappings are instantiated; the stage occurs after the response-selection mechanism becomes available to Task 2 and before response selection begins in Task 2. If this stage took longer in older adults, an overadditive interaction with SOA of the sort that was found would be expected. In Experiment 7, older adults were more slowed than younger adults in Task 2 by having to execute a motor response in Task 1. The interactions of age group and SOA with the complexity of the response mapping in Task 1 and with whether or not a motor response was required in Task 1 both approached significance. Once again, if there is a small but real effect, the findings may be the result of a lengthening in older adults of a processing stage concerned with instantiating motor programs, or they may be the result of a reduced capacity in older adults to organize and execute similar motor programs. Because the task-switching model generally provides a better account of the results, and an additional processing stage fits comfortably with that model, it is tempting to adopt that alternative. The available evidence, however, does not permit a clear choice between the two theoretical alternatives, an additional instantiation stage and a reduced specific capacity.

There is one additional place we might look for evidence that older adults are selectively impaired in managing dual tasks, when the two tasks were separated by the maximal SOA, 1,000 ms. The costs of managing two tasks, even when there is no overlap between the tasks, can be measured by subtracting the RT when the task was done alone from the RT when the task was done in the dual-task context. These costs were calculated for every condition in every experiment where that was possible. First, consider Task 1. Even if the stimulus for Task 2 does not appear until the response is given in Task 1, throughout the processing of Task 1 the expectancy of Task 2 must be maintained, and the response mappings for Task 2 must be held in readiness. The average cost of performing Task 1, the color task, in the dual-task context relative to the same task performed alone was 175 ms for younger adults and 162 ms for older adults; the difference was not significant, $t(13) = -0.78$, *ns*. The results provide no support for an assertion that older adults are impaired in maintaining preparation for Task 2 while Task 1 is being carried out. Moreover, because older adults are assumed to be slowed, and general slowing would result in greater costs for older adults, the results are consistent with an assertion that older adults are less affected by the dual-task demands. Next, consider Task 2. When the two tasks are widely separated, there are no processing demands of Task 1. A general dual-task set must be maintained, and the mapping rules for Task 1 must be retained, but otherwise all processing resources can be devoted to Task 2. The average cost of performing Task 2, the letter or number identification task, in the dual-task context relative to the same task performed alone was 115 ms for younger adults and 170 ms for older adults; this difference was significant, $t(11) = 3.11$, $p = 0.01$. This is a very modest difference, smaller than would be expected from general slowing. In addition, for some older participants on some trials in some conditions, the response to Task 1 would not have been given before the 1,000-ms SOA expired and the stimulus for Task 2 appeared, so the two tasks would overlap. Nevertheless, we cannot completely exclude the interpretation that older adults require slightly longer or are slightly less able to clear out the Task 1 set and devote processing to Task 2.

The evidence from these experiments is inconsistent with assertions that older adults suffer a diminution in some general cognitive resource, resulting in a general impairment in the ability to manage two overlapping tasks (e.g., Crossley & Hiscock, 1992). The evidence is consistent with a task-switching model in which the architecture of task management is the same in younger and older adults, except that older adults are slowed. It seems likely that other researchers have reached the conclusion that performance is impaired in older adults because of a diminished resource because they have used complex tasks involving multiple operations and have exerted little control over the scheduling of the tasks (see Brainerd & Reyna, 1989, for a similar argument concerning inferences about the growth of cognitive resources in children). The present experiments have used simple, well-specified tasks and have carefully controlled the overlap between the tasks. It may be that more complex tasks activate executive processes not called on in the present tasks and that these processes are particularly impaired in old age. Alternatively, it may be the variability in the actual collision between the tasks obscures the results, causing limited and focused changes with age to appear widespread and nonspecific.

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