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Aging and time-sharing aspects of executive control

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A particularly important aspect of executive functioning involves the ability to coordinate two simultaneous activities. The role of this aspect of executive functioning in adult-age differences in cognitive performance was examined in a study involving 150 adults between 20 and 91 years of age who performed the same visual–motor tracking task with three different primary tasks. The participants also performed several additional cognitive tasks that allowed examination of the relation of time-sharing efficiency to other types of cognitive functioning. The results were consistent with the existence of a distinct time-sharing ability because the time-sharing costs in the three dual-task combinations were significantly correlated with one another but only weakly correlated with other cognitive variables. Increased age was associated with reductions in time-sharing ability, and greater efficiency in performing two tasks at once was associated with better performance on tasks assessing spatial, reasoning, and memory abilities. Although this pattern is what one would expect if executive processes contribute to age differences in cognitive functioning, the effects were smaller than those associated with a perceptual speed construct.

Executive processes are cognitive processes responsible for the planning, coordination, and monitoring of other cognitive operations. Because the efficiency of processes responsible for controlling other cognitive operations is likely to be an important determinant of performance in a wide variety of cognitive tasks, executive functioning can be hypothesized to be a critical factor in individual differences, and particularly age-related individual differences, in cognitive functioning. That is, the performance of many different types of cognitive tasks might be expected to be disrupted if the control and coordination of relevant cognitive processes is impaired with increased age. However, progress in investigating executive functioning has been hampered because although there is some agreement about the processes that might be involved in executive functioning (e.g., Smith & Jonides, 1999), there is little consensus about how they are best assessed.

One approach to the investigation of executive processes has relied upon various neuropsychological tests such as the Wisconsin Card Sorting Test, the Tower of Hanoi, Trail Making, Stroop Interference, and various fluency tests to assess executive processes. Unfortunately, correlations among the measures from these tasks have typically been quite low relative to correlations with "nonexecutive" measures (e.g., Andres & van der Linden, 2001; Della Sala, Gray, Spinnler, & Trivelli, 1998; Duncan, Johnson, Swales, & Freer, 1997; Kafer & Hunter, 1997; Kopelman, 1991; Kramer, Lavish, Weber, & Bardell, 1999; Lehto, 1996; Robbins et al., 1998; Robbins et al., 1997; Salthouse, Fristoe, & Rhee, 1996; but see Hanes, Andrewes, Smith, & Pantelis, 1996, for an exception), and thus there is little evidence that they represent a unitary construct.

The present study relies on a strategy recently described by Salthouse (2001b) in which multiple measures of a specific aspect of executive functioning are obtained, and then the relations of the measures are determined to each other, to an individual difference characteristic such as age, and to measures of other types of cognitive functioning. The strategy can be illustrated with reanalyses of data from several earlier projects (see Table 1 for citations) investigating inhibition and task-switching aspects of executive functioning. In each study, adults across a wide range of ages performed either two or three tasks designed to assess the relevant aspect of executive functioning, as well as tasks assessing perceptual speed and other types of cognitive functioning. The executive functioning measures were based on difference scores to represent the processing associated with inhibition (i.e., Stroop incongruent time minus Stroop congruent time) or with task switching (i.e., time on trials in which switching was required minus time on trials in which no switching was required). The major questions that the strategy was designed to address are as follows: (1) Is there evidence of a coherent construct corresponding to the hypothesized aspect of executive functioning? (2) Is the construct related to age in the expected direction? (3) How strong are the unique relations of that construct to other measures of cognitive functioning?

All three questions can be examined in the context of a structural equation model such as that portrayed in Figure 1.

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Table 1
Results of Structural Equation Analyses of Prior Studies of Aging and Executive Processes Using the Model in Figure 1

Executive Process	Study	Path A	B	C	D	E	F	$\chi^2(df)$	CFI
Inhibition	1	−.73	.18	.52	−.46	.30	−.33	22.06(15)	.988
Switching	2	−.68	.04	.56	−.58	.70	−.24	29.29(22)	.985
Switching	3	−.62	−.04	.55	−.60	.51	−.20	12.46(15)	1.00
Switching	4	−.67	−.48	.59	−.41	.59	.16	15.08(15)	1.00
Switching	5	−.66	−.38	.40	−.40	.61	.07	29.02(15)	.977

Note—Values in parentheses are not significantly ($p < .05$) different from zero. Ratios of $\chi^2(df)$ less than 2 and CFI values close to 1.0 are usually considered indications of good fit of the model to the data. Studies: (1) Salthouse and Meinz (1995), $N = 242$. Executive Processes: Incongruent time minus congruent time for Color Stroop, Position Stroop, and Number Stroop. Speed: Letter Comparison and Pattern Comparison. Cognition: Computation Span and Reading Span tests of working memory. (2) Salthouse, Fristoe, McGuthry, & Hambrick (1998), $N = 161$. Executive Processes: Switch Reaction time minus no-switch reaction time for right/left, more/odd, and add/subtract tasks. Speed: Letter Comparison and Pattern Comparison. Cognition: Ravens, Cube Assembly, and Free Recall. (3) Salthouse et al. (2000), $N = 207$. Executive Processes: Alternation time minus repetition time in a variant of the Trail Making Test (i.e., Connections Test). Speed: Letter Comparison and Pattern Comparison. Cognition: Ravens, Spatial Relations, and Paired Associates. (4) Salthouse (2001a, Study 1), $N = 220$. Executive Processes: Alternation time minus repetition time in a variant of the Trail Making Test (i.e., Connections test). Speed: Letter Comparison and Pattern Comparison. Cognition: Ravens, Locations, and Figural Classification. (5) Salthouse (2001a, Study 2), $N = 229$. Executive Processes: Alternation time minus repetition time in a variant of the Trail Making Test (i.e., Connections Test). Speed: Letter Comparison and Pattern Comparison. Cognition: Analytical Reasoning, Locations, and Figural Classification.

For example, evidence of construct validity would be provided if indicators of the executive processing construct (i.e., E1, E2, and E3) had strong relations to that construct, but the relations between the executive processes construct and other constructs (e.g., Path D) were substantially less than one. The relation of the executive process construct to age would be apparent in the coefficient for the path from age to that construct (i.e., Path C). Finally, the unique contribution of the executive processes construct to other types of cognitive functioning would be evident in the coefficient for the path from that construct to the cognition construct when the influences of other constructs are taken into consideration (i.e., Path F).

Because structural equation models are equally applicable to variables derived from experimental paradigms or neuropsychological tasks as to variables obtained from psychometric tests, it is important not to confuse the analytical method with the procedures used to collect the data being analyzed. Structural equation models have several advantages over more typical methods of analyzing data in studies of aging and cognition. The primary advantage of structural equation models in the present context is that they allow assumptions that are usually implicit to be explicitly articulated and tested. To illustrate, most researchers interested in cognitive aging probably assume that the particular variable they are investigating represents a broader construct, and that the construct is somehow involved in the mediation of age-related differences in other cognitive variables. The validity of these assumptions is seldom examined, but one method of subjecting them to empirical tests is to specify them as explicit hypotheses in a structural model. Of course, a discovery that a model provides a good fit to the data does not mean that the model and its associated hypotheses are confirmed, because other models with different hypotheses might provide equally good fits. However, only by explicitly specifying the assumptions as hypotheses do they have an opportunity to be falsified. Furthermore, by including all relations among theoretical constructs in a structural model, it is possible to estimate the relative magnitude of each hypothesized relation rather than merely determining whether it was or was not statistically significant. The major challenges of structural equation models in this type of application are that moderately large samples of participants are required to ensure reasonably precise estimates of the model parameters, and that a considerable amount of data must be obtained from each participant to ensure reliable assessment of all variables included in the models.

The parameter estimates resulting from the application of the model in Figure 1 to five separate data sets are summarized in Table 1. Although not presented in the table, the standardized coefficients for the relations between the latent constructs and the observed variables (i.e., the paths from the circles to the squares in the figure) were all greater than .43, with a median of .75. This information, together with the good fits of the models to the data (Table 1), implies that in each data set there were coherent constructs corresponding to a hypothesized aspect of executive functioning, to perceptual speed, and to other types of cognitive functioning. The entries in column C in Table 1, represent-

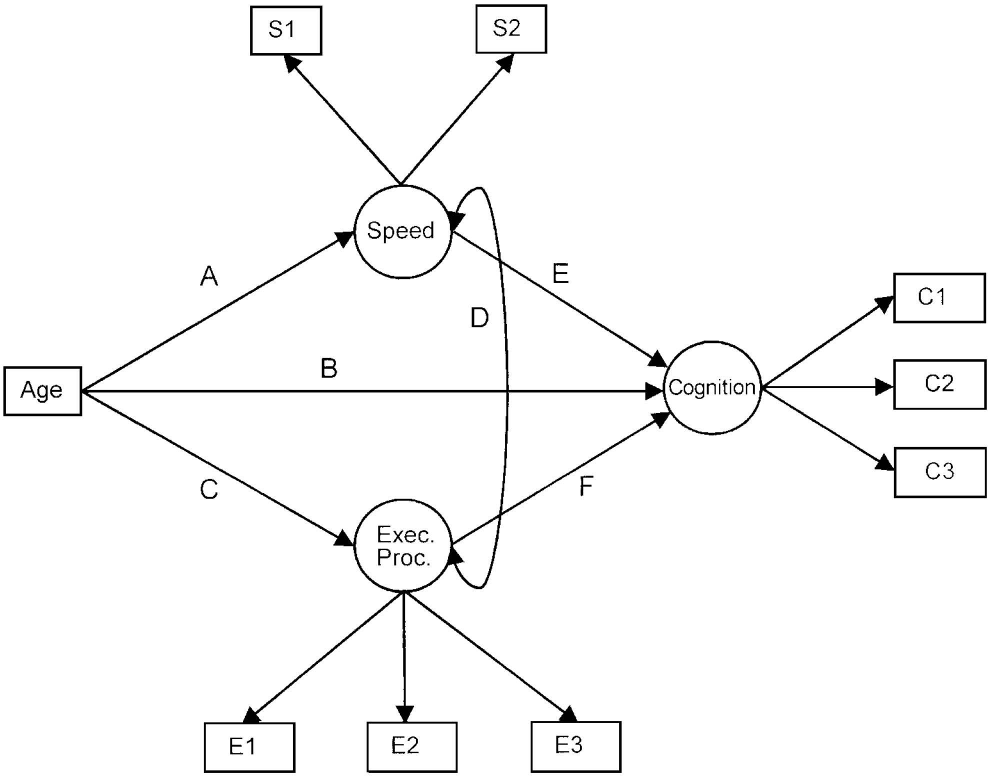

Figure 1. Schematic structure of relations among age, and constructs representing executive processes, processing speed, and other aspects of cognitive functioning.

ing the coefficients for the path from age to the hypothesized executive functioning construct, ranged from .40 to .59. Because all of the executive process variables were difference scores and larger differences represent poorer executive functioning performance, these results indicate that increased age was associated with reduced efficiency of inhibition and of task switching. However, for the four data sets with a task-switching construct, the entries in column F were not significantly different from zero, and thus there is no evidence of a unique relation between switching efficiency and other types of cognitive functioning. The coefficient for Path F was significantly different from zero with the Stroop-based inhibition construct, and hence this aspect of executive processing does appear to have a relation to working memory independent of any effect through the perceptual speed construct.

The results summarized in Table 1 imply that although it is meaningful to refer to a construct reflecting switching aspects of executive functioning, that construct does not appear to be involved in the mediation of age differences in cognitive performance because of the absence of a unique relation to measures of cognitive functioning. The Stroop-based inhibition construct is more plausible as a partial mediator of adult-age differences in working memory, but any conclusion must be tentative because relevant results are available for only one study.

The goal in the present project was to apply the strategy just outlined to investigate time-sharing aspects of executive processing. In some respects, time-sharing ability can be considered a prototypical executive process because it refers to the effectiveness of coordinating two simultaneous activities, distinct from the efficiency of performing either activity by itself. Although many studies have investigated time sharing with one particular combination of tasks, only a few studies have examined correlations among time-sharing performance across different combinations of tasks to determine whether some people are generally better than others at simultaneously performing two or more activities. This latter information is important because unless there is evidence of at least moderate correlations among measures of time-sharing performance in different sets of tasks, it may be more appropriate to refer to separate proficiencies in performing particular combinations of tasks rather than a unitary time-sharing ability.

The most frequently used analytical procedure to investigate the possibility of a time-sharing ability has involved some form of factor-analytic methodology. The assumption has been that if a time-sharing ability exists, then individual differences in performance in dual-task situations would be expected to be distinct from individual differences in performance on the same tasks when they are performed alone. That is, a factor representing dual-task performance should be identified that is separate from any factors corresponding to single-task performance.

Unfortunately, results from previous research employing factor-analytic methods with time-sharing variables have been inconsistent. To illustrate, there have been claims of several time-sharing factors (e.g., Brookings, 1990; Jerneic & Sverko, 1994), of a single time-sharing factor (e.g., Fogarty & Stankov, 1982), and of no time-sharing factor (e.g., Fogarty, 1987; Fogarty & Stankov, 1988; Stankov, 1988). In addition, because correlations between performance measures in a divided-attention condition were no different from correlations between the performance measures in a single-task condition, Lansman, Poltrock, and Hunt (1983) concluded that performance in a situation that requires division of attention is determined almost entirely by one's ability to deal with a single task.

A number of reasons have been proposed to account for the mixed outcomes from prior factor-analytic research concerning the existence of a time-sharing ability (e.g., Ackerman, Schneider, & Wickens, 1984; also see Somberg & Salthouse, 1982). Among these are the following: (1) different combinations of tasks across studies, including some with the same modalities of input and output and thus the potential for structural interference; (2) inconsistent treatment of single-task performance in the analyses; (3) variability in the effectiveness of controlling task emphasis or tradeoff; (4) differences in the continuous nature of one or both tasks, which may allow switching of attention instead of division of attention; (5) differences in the method of assessing dual-task performance (e.g., differences, ratios, residuals, or factor scores); (6) use of small samples, resulting in low precision of the correlations among variables; (7) unknown reliability of the measures of dual-task performance; and (8) few attempts employing convergent and discriminant validity methods to investigate the construct validity of a time-sharing factor.

Several of these characteristics are particularly problematic for the assessment of time-sharing ability. For example, without some control of individual differences in single-task performance, it is difficult to determine whether performance in the dual-task conditions merely reflects the ability to perform each task in isolation, rather than the ability to perform them in combination. Furthermore, unless task emphasis is rigorously controlled, time-sharing costs could be manifested in either or both of the simultaneously performed tasks, making it difficult to interpret the results from separate analyses conducted on the measures in each task.

In the present study, participants across a wide range of ages performed three different primary tasks both alone and together with the same visual–motor secondary task. Only a single secondary task was used to maximize the possibility of detecting a distinct time-sharing ability. That is, one possible reason for the low correlations among time-sharing measures in prior studies may have been that the various combinations of tasks differed in dimensions unrelated to the ability to perform two tasks simultaneously, such as stimulus encoding requirements, response selection demands, and so on, and that these differences obscured the influence of a general time-sharing ability. An assumption of the present approach is that the effects of these other factors might be minimized by using only a single secondary task. Of course, a limitation of this approach is that any time-sharing ability that might be identified could be quite narrow, and possibly restricted to these primary tasks and one particular visual–motor tracking task. However, in view of the inconsistent results from prior research, the discovery of even a narrow time-sharing ability would be important in establishing the existence of an individual difference characteristic related to the efficiency of simultaneously performing two activities.

The participants performed the secondary task alone in two prior sessions as well as earlier in the same session, and the difficulty of the secondary task was adjusted prior to the administration of the dual tasks so that each individual's performance was within the same approximate range. In an attempt to increase generalizability, the three primary tasks were selected to represent distinct cognitive abilities. That is, a paired-associate memory task involving unrelated words was assumed to assess episodic memory, a numeric series completion task was assumed to assess inductive reasoning, and a spatial directions task was assumed to assess spatial visualization ability.

The present approach to the investigation of individual differences in time-sharing ability addresses several of the problems noted above: (1) Structural interference associated with the same input or output modality was minimized because the primary tasks involved auditory stimuli and vocal responses, whereas the secondary task involved visual stimuli and manual responses; (2) use of the same secondary task may reduce other influences on dual-task performance and possibly increase the likelihood of detecting a time-sharing ability; (3) time-sharing effectiveness is evaluated by comparing dual-task performance with single-task performance after attempting to equate everyone on level of secondary task performance; (4) because the secondary task had been previously performed alone and was no longer novel, it might be more likely to be treated as the background activity; (5) the effects of performing two tasks at once were examined separately in each task, and in a composite measure reflecting average time-sharing costs across the two tasks; (6) because the target moved randomly and its position was updated every 20 msec, the secondary task required continuous demands on attention; (7) reliability was assessed for each measure of time-sharing performance; and (8) secondary task performance can be decomposed to help identify which specific aspects of performance are impaired during performance of a concurrent task.

Because the participants in this study also performed other cognitive tasks across the three sessions of the project, several variables were used to examine the structural model illustrated in Figure 1. Specifically, general cognitive functioning was assessed with variables representing reasoning (analysis–synthesis), spatial (block design), and episodic memory (recall across four trials) abilities; perceptual

Table 2
Characteristics of the Participants

Characteristic	*M*	*SD*	Range	Age Correlation
Age	50.4	17.0	20–91	–
% females	65	–	–	–
Self-rated health	2.0	0.8	1–4	.29*
Years of education	15.9	2.6	11–25	.07
WAIS–III scaled scores				
Vocabulary	13.4	3.3	3–18	.05
Block Design	11.6	3.4	4–19	−.03
Digit Symbol	12.2	2.9	6–18	−.11

Note—Self-rated health was on a scale from 1 (*excellent*) to 5 (*poor*). WAIS III scaled scores are age-adjusted scores derived from Table A.1 in Wechsler (1997a). These scaled scores have a mean of 10 and a standard deviation of 3.

speed was assessed with choice reaction time and scores from the cross out and digit symbol tests.

METHOD

Participants

Descriptive characteristics of the 150 participants are presented in Table 2. Participants were generally high functioning, with an average of over 16 years of education and age-adjusted scores on standardized tests between .5 and 1 *SD* above the means from the nationally representative normative sample. Additional tasks performed in the project are described elsewhere (Salthouse, Berish, & Miles, in press; Salthouse & Ferrer-Caja, 2002). Nearly all of the participants completed the three sessions of the project within 3 weeks, and the median interval between the first and the third sessions was 8 days.

Procedure

The visual–motor tracking task was performed on three sessions, with a 20-sec practice trial and five 70-sec experimental trials on each session. The task involved the research participant manipulating a trackball with his/her dominant hand to attempt to keep a cursor (a plus sign) on a randomly moving target (a solid circle). Motion of the target was determined randomly in both the *x*- and *y*-dimensions, and because the positions were updated every 20 msec, the target had a jittering appearance. The size of the average shift in target position could be adjusted by the experimenter, and for the baseline tracking conditions it was approximately equal to the diameter of the target. At a viewing distance of 60 cm, the size of both the target and cursor were about 0.5° of visual angle. The primary measure of tracking performance was the average discrepancy between the target and cursor in *x*-, *y*-coordinate space, assessed by the root-mean squared error (RMSE) in pixels across the 70-sec interval.

Immediately prior to the dual-task testing on the third session of the project, the difficulty of the tracking task was individually adjusted for each research participant by altering the average magnitude of the shift in target position to achieve an RMSE of between 40 and 50 (corresponding to approximately 1.0° of visual angle). That is, one of the factors contributing to difficulty in tracking was the average size of the change in target position from one 20-msec interval to the next, with larger changes corresponding to greater difficulty. The average change in position was therefore increased if the individual's error in the preceding trial was less than 40, and it was decreased if the error was greater than 50. The adjustment trials, which were each 20 sec in duration, were repeated until the RMSE was within the target range.

Following the adjustment phase, the single- and dual-task conditions were administered first with the directions primary task, next with the series completion primary task, and finally with the paired-associates primary task. The same sequence of trials was followed for each primary task and consisted of one trial of tracking alone, one trial of the primary task alone, six trials of performing the primary task and the tracking task together, one trial of the primary task alone, and one trial of tracking alone. In the dual-task conditions, the primary task started 5 sec after the secondary task began, and finished 5 sec before the secondary task ended. Each primary task involved the presentation of auditory stimuli through a pair of speakers, and vocal responses that were recorded by the examiner. Participants were instructed to emphasize performance on the primary task but also to perform the secondary task as well as possible given that constraint.

Directions primary task. This task, adapted from a task described by Craik and Dirkx (1992), involved the auditory presentation of a direction (e.g., North, South, East, West) followed by four direction shifts (e.g., right, left, back, front) and the word *now*. After the word *Now*, the participant was instructed to say the current direction. For example, a problem might consist of the following: "West—right—right—back—left—Now." The correct answer in this case would be "South." The items were presented every 2 sec, with a 7 sec interval between successive trials.

Series completion primary task. In this task, five numbers were auditorily presented followed by "Next," which indicated that the participant should say the number that would come next in the sequence. The items were presented every 1.75 sec, with a 5 sec interval between successive trials. The problems were based on those described in Salthouse and Prill (1987), with two first-order progression problems, two alternation problems, and one second-order progression problem in each block of five problems. An example of a second-order progression problem is: "5—7—10—14—19—Next." The correct answer to this problem would be "25" because the magnitude of the increment increased with each successive item.

Paired-associates primary task. Participants in this task listened to a set of word pairs and then tried to recall the second member of the pair when presented with the first. Six pairs of words were auditorily presented with a 4-sec interval between successive pairs, followed by the first member of each pair at 5 sec intervals. All words were concrete nouns of at least moderate frequency. The dependent variable was the number of response words correctly recalled to the appropriate stimulus words.

The speed tests involved the participant crossing out symbols identical to a target symbol (Cross Out; Woodcock & Johnson, 1990), and substituting symbols for digits according to a code table (Digit Symbol; Wechsler, 1997a). Choice reaction time was measured as the median reaction time across 60 trials in which manual responses (press of Z, C, B, or M keys) were made to visually displayed stimuli (an X in one of four horizontal boxes). The memory test was the number of words recalled across four trials of the same 12-word list (Word Lists; Wechsler, 1997b), the reasoning test involved the participant determining the logical rule relating elements to one another (Analysis–Synthesis; Woodcock & Johnson, 1990), and the spatial test involved the participant assembling blocks to match specified patterns (Block Design; Wechsler, 1997a).

RESULTS

Two error measures were derived from the analyses of tracking performance. The primary measure was total error, which consisted of the RMSE in pixels between the *x*, *y* coordinates of the target and cursor positions. A second measure was the lag-adjusted error, which was the residual error after adjusting for the response lag of the participant. It was derived by shifting the vector representing the

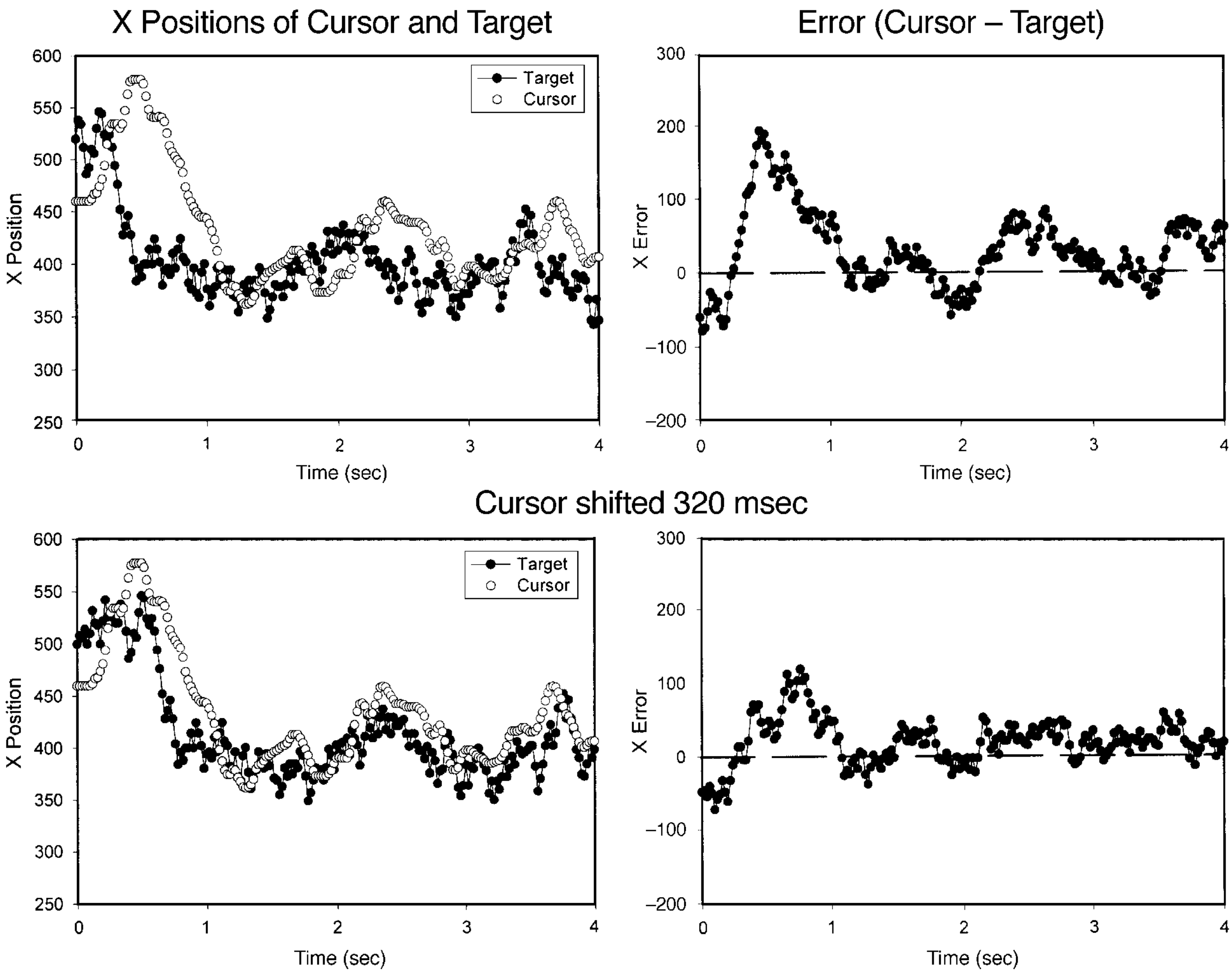

Figure 2. Schematic illustration of error along the *x*-axis before (top panels) and after (bottom panels) adjusting for response lag. In this example, the minimum residual error occurred when the cursor position was shifted 320 msec.

cursor position along the time axis until the RMSE between target and shifted cursor position was at its minimum (Figure 2). Because the two types of errors were highly correlated ($r > .9$), the second value was expressed as a proportion to indicate the magnitude of reduction in error associated with the lag adjustment. That is, the lag-adjusted proportional reduction was 1 − (lag-adjusted error/total error), and thus a higher proportion corresponded to a larger reduction in error associated with the adjustment for response lag.

The response lag was computed separately on both the *x*- and *y*-axes. The mean *x* lag was about 25 msec shorter than the mean *y* lag, suggesting that movements were faster in the horizontal direction than in the vertical direction. However, the two lags were highly correlated in all conditions (i.e., $r > .85$), and therefore only the *x* lag was used in the error adjustments.

Means and age correlations for the primary and secondary task performance measures in the alone and dual conditions are presented in Table 3. The entries in the top of the table indicate that increased age was associated with lower levels of performance in each task. Surprisingly, performance in the directions task was significantly higher in the dual condition than in the alone condition. This effect cannot be attributed to simple practice because the order of the alone and dual trials was counterbalanced for each participant; it may be due to greater arousal or motivation in the dual-task condition. There was no difference between the alone and dual performance for the paired-associates task, but with the series completion task, performance in the dual condition was significantly lower than in the alone condition.

Mean tracking error in the single-task trials at the beginning of Session 3 was 69.67, and the average error across the three sets of tracking alone trials was 53.82. The mean size of the target position shift after the individual adjustment of tracking difficulty was 18.8, and this value had a correlation of −.42 with age. Examination of the values in Table 3 reveals that the adjustment of tracking difficulty was successful in eliminating age relations in the tracking-

Table 3
Primary and Secondary Task Performance in the Alone and Dual Conditions

Task	Alone			Dual			
	M	*SD*	Age *r*	*M*	*SD*	Age *r*	*t* value
Primary Task							
Directions (max = 5)	3.50	1.51	−.40*	3.78	1.33	−.36*	−5.17*
Series completion (max = 5)	3.14	1.15	−.37*	3.01	0.98	−.38*	2.42*
Paired associates (max = 6)	2.80	1.67	−.48*	2.77	1.71	−.52*	0.30
Secondary Task (Tracking)							
Directions							
Total error	54.17	5.94	.01	60.31	10.86	.21*	−8.43*
x lag	293	65	.08	315	92	.15	−4.25*
Lag reduction	0.31	0.08	−.46*	0.22	0.09	−.50*	19.09*
Series completion							
Total error	53.52	5.74	.03	57.89	7.91	.19*	−8.51*
x lag	299	57	.09	318	87	.15	−4.89*
Lag reduction	0.31	0.08	−.42*	0.24	0.09	−.44*	17.67*
Paired associates							
Total error	53.83	6.08	−.00	58.15	10.43	.18*	−6.45*
x lag	301	58	.05	312	69	.15	−4.55*
Lag reduction	0.31	0.08	−.41*	0.25	0.09	−.44*	15.64*

Note—Lag reduction is the proportional reduction in error after adjusting for the response lag, i.e., Lag reduction = 1 − (lag-adjusted residual error/total error). *Values significant at $p < .01$.

alone conditions, although there was a significant relation between age and tracking error in each dual-task condition.

The values in Table 3 indicate that for each primary task, tracking error was significantly larger in the dual conditions than in the alone conditions. The average *x* lag (in milliseconds) was longer in the dual conditions than in the alone conditions, and the proportional reduction in error after adjusting for response lag was significantly smaller in the dual conditions than in the alone conditions.

Increased age was associated with greater total error in the dual-task conditions and smaller proportional reduction in error in each task/condition combination. These results indicate that, relative to young adults, older adults were overall less successful in tracking while concurrently performing another task, and even after adjusting for response lag were less precise in maintaining a correspondence between target position and cursor position.

Reliabilities of, and correlations among, the difference scores for the primary and secondary tasks are presented in Table 4. It can be seen that the estimated reliabilities of the primary task difference scores were very low, but that the estimated reliabilities for the tracking difference scores were quite respectable. Perhaps because of the low levels of reliability, none of the correlations among the primary task difference scores were statistically significant. There were also no significant correlations between the difference scores for corresponding primary and secondary tasks, and thus there is no evidence of a between-person tradeoff in the performance of the two tasks. However, the correlations among the tracking difference scores were in the moderate to large range, which indicates that there is consistency across individuals in the amount of disruption in secondary performance when they are performing different primary tasks.

Time-sharing performance in Table 4 is represented in terms of difference scores because they are the most familiar, but it could also have been expressed in terms of either ratios or regression-based residuals between performance in the alone and dual conditions. However, examination of these other measures revealed that the pattern of results was very similar with each index of time-sharing performance. To illustrate, correlations between the ratios of tracking error with directions and series completion, directions and paired associates, and series com-

Table 4
Correlations Among Difference Scores

Task	1	2	3	4	5	6	*M*	*SD*
1. Directions—Primary	(.06)	–	–	–	–	–	−0.28	0.67
2. Series Comp.—Primary	.05	(.33)	–	–	–	–	0.13	0.65
3. Paired Assoc.—Primary	−.09	.01	(.18)	–	–	–	0.03	1.08
4. Directions—Track RMSE	−.17	−.10	−.03	(.68)	–	–	6.14	8.89
5. Series Comp.—Track RMSE	−.10	−.16	−.02	.51*	(.72)	–	4.37	6.29
6. Paired Assoc.—Track RMSE	−.12	−.11	.05	.36*	.68*	(.78)	4.31	8.19

Note—Reliabilities of the difference scores (in parentheses along the diagonal) were estimated by boosting the correlation between the difference for the first set of trials (i.e., the first alone trial minus the average of the first three dual-task trials) and the difference for the second set of trials (i.e., the last alone trial minus the average of the second three dual-task trials) by the Spearman–Brown formula. *Values significant at $p < .01$.

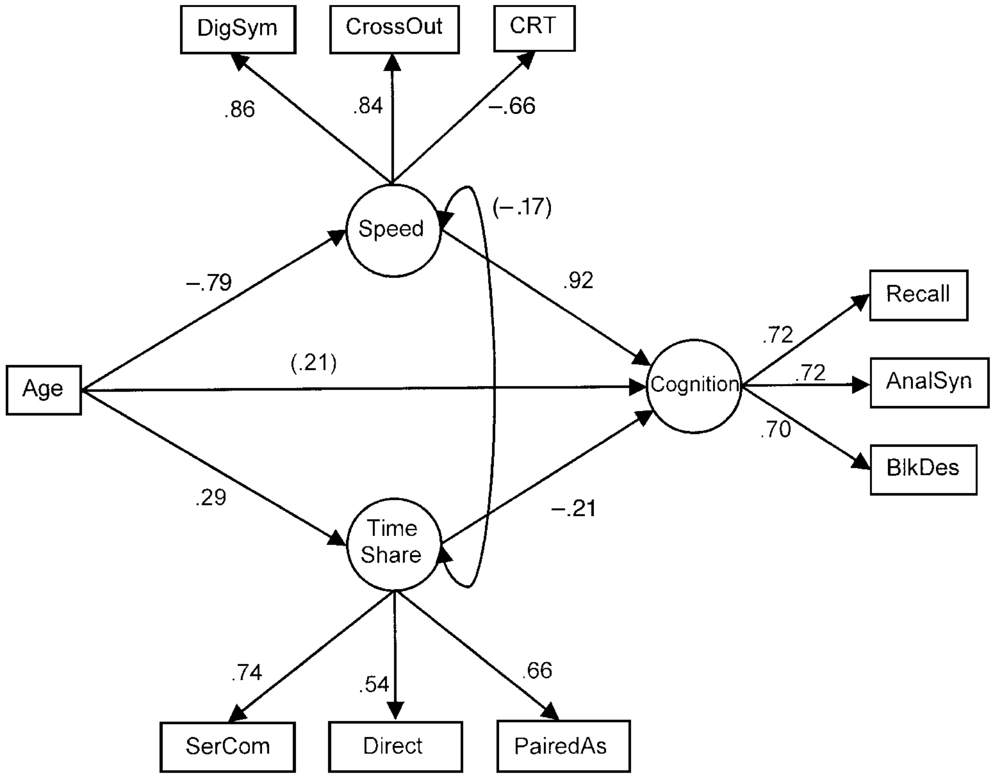

Figure 3. Structural model with standardized regression coefficients for relations among age, time-sharing construct, processing speed construct, and a construct representing general cognitive functioning. Numbers in parentheses were not significantly different from zero.

pletion and paired associates were .49, .37, and .67, respectively, and for residuals (i.e., partialing single-task performance from dual-task performance) they were .52, .35, and .57, respectively.

Because of the possibility that, despite the instructions, participants may have differed with respect to the relative emphasis allocated to the two tasks during the dual-task conditions, separate analyses of time-sharing performance in each task are potentially misleading.[1] The following procedure was therefore used to create a composite measure of time-sharing costs as a means of integrating the costs in the two tasks. First, the scores in the alone and dual conditions were expressed in standard deviation units based on scores in the alone condition. Next, separate time-sharing costs were derived for the primary task and for the secondary task. The primary task cost was the difference between scores in the alone and dual conditions (i.e., alone − dual), but because higher scores in the secondary tracking task represent poorer performance, the secondary task cost was computed by reversing the direction of the subtraction (i.e., dual − alone). Finally, because the primary and secondary time-sharing costs were expressed in a common metric of standard deviation units of the alone condition, they were averaged to create a composite time-sharing cost. These composite time-sharing costs were all significantly correlated with one another (i.e., directions–series completion, $r = .42$; directions–paired associates, $r = .27$; and series completion–paired associates, $r = .52$), and were used in the following analyses. It should be noted, however, that very similar results were obtained in all subsequent analyses when the tracking difference scores were used as the measures of time-sharing performance.

Structural equation models were examined for the structure portrayed in Figure 1 with the composite time-sharing costs serving as the measures of executive functioning, two paper-and-pencil speed variables (Cross Out and Digit Symbol) and a choice reaction time variable serving as the measures of processing speed, and memory (free recall over four trials), reasoning (analysis–synthesis), and spatial ability (block design) variables serving as the measures of other cognitive functioning. The model provided a good fit to the data (i.e., $\chi^2 = 72.88$, $df = 30$, CFI = .979); standardized coefficients for the relations in the model are displayed in Figure 3. Time-sharing performance is measured in costs, and thus larger values reflect poorer time-sharing performance. A positive correlation with age would therefore indicate that increased age was associated with poorer time-sharing performance, and a negative correlation with the cognition measures would indicate that better time-sharing performance was associated with higher levels of cognitive functioning.

The results portrayed in Figure 3 are consistent with the existence of a coherent time-sharing construct, as reflected by the sizable interrelations among the composite time-sharing costs across three different primary tasks. That is, the standardized coefficients from the time-sharing construct to the time-sharing costs ranged from .54 to .74, indicating that they were all moderately related to one another. Furthermore, this executive functioning construct was not significantly related to a perceptual speed construct, and thus it can be considered to exhibit discriminant validity. However, the time-sharing construct had a positive relation to age, and a negative relation to the construct representing other types of cognitive functioning.[2]

Because the participants also performed additional cognitive tasks, the structural equation analysis was repeated with the cognition construct based on variables from four different tasks (i.e., Raven, 1962; letter series, Noll & Horn, 1998; Spatial Relations, Bennett, Seashore, & Wesman, 1997; and paper folding, Ekstrom, French, Harman, & Dermen, 1976). The results of this analysis were very similar to those in Figure 3. That is, the standardized coefficients for the paths to the cognition construct were .18 for age, .85 for speed, and −.18 for time sharing. Fit statistics for this model were also comparable to the model with the other indicators of the cognition construct [i.e., $\chi^2(39) = 83.78$, CFI = .988].

To maximize comparability with the studies reported in Table 1, the original structural analysis was repeated with only the letter comparison and pattern comparison (Salthouse & Babcock, 1991) variables serving as the speed measures. Once again the results were very similar to those portrayed in Figure 3. The model had a good fit to the data [i.e., $\chi^2(22) = 49.34$, CFI = .992], and the age–speed (−.74) and speed–cognition (.61) coefficients were large, but the age-cognition coefficient (−.08) was small. The covariation between speed and the time-sharing construct was also small (−.14), but there were moderate relations from age to time sharing (.29) and from time sharing to cognition (−.24).

DISCUSSION

As noted in the introduction, the results from prior research have been inconsistent with respect to existence of a distinct time-sharing ability. A separate time-sharing ability has been inferred on the basis of differential effects of practice on performance across single- and dual-task conditions, and from the existence of positive transfer of dual-task performance to new combinations of tasks (e.g., Damos & Wickens, 1980; Kramer & Larish, 1996; Kramer et al., 1999). However, outcomes from factor-analytic studies investigating time-sharing abilities have been mixed.

The results of the present study support the existence of a coherent individual differences construct representing time-sharing aspects of executive processes because the amount of disruption in tracking associated with the performance of one primary task was correlated with the amount of disruption associated with the performance of other primary tasks. Not only was there evidence of convergent validity, in the form of moderate correlations of the time-sharing difference scores (and composite time-sharing costs) with one another, but there was also evidence of discriminant validity because the time-sharing variables had weak correlations with variables representing other constructs. Furthermore, the structural equation analyses revealed that there was a good fit to the data with a structural model in which the time-sharing variables represented a single factor that was distinct from factors representing perceptual speed and other facets of cognitive functioning. This pattern is similar to those of the studies investigating inhibition and task-switching aspects of executive functioning summarized in Table 1. However, the present results differ from those of the earlier studies in that the construct representing time-sharing aspects of executive functioning was not related to perceptual speed, and it was significantly related to the measures of cognitive functioning after taking relations of age and perceptual speed into consideration.

Although these results are consistent with the view that time-sharing aspects of executive functioning are involved in the mediation of age-related differences in cognitive functioning, it should be noted the mediating effects are small relative to those associated with the perceptual speed construct. This is apparent in the magnitude of the coefficients for each construct from age and to the cognition construct in Figure 3, and in the relative attenuation of the age–cognition relations in multiple regression analyses. With respect to the latter, age was associated with 25.4% of the variance in the cognitive composite, but this quantity was reduced to 0.1% after statistical control of the perceptual speed composite, and was only reduced to 17.5% after control of the time-sharing composite. Furthermore, this pattern does not appear to be restricted to a particular combination of speed variables because very similar results were obtained when the perceptual speed construct was based on two paper-and-pencil comparison tasks (i.e., age was associated with only 4.2% of the variance in the cognitive composite after statistical control of the composite based on letter comparison and pattern comparison). The processes involved in the perceptual speed construct therefore appear to be more closely linked with both age and other types of cognitive functioning than are the (presumably executive) processes involved in time sharing. Unfortunately, only relative statements of this type can be made at this time because the nature of the perceptual speed construct is still poorly understood.

What is responsible for the disruption in tracking performance when another task is performed at the same time? The detailed analyses of tracking performance provide some clues because a similar pattern of tracking disruption was evident across the different primary tasks. In every case, there was an increase in the average delay or lag in responding to changes in target position, and there was a greater residual error after adjusting for this lag. This pattern suggests that division of attention not only slowed down the rate of responding to the tracking target, but it was apparently also associated with lower temporal and spatial precision. That is, the residual error after adjusting for response lag could reflect poorer temporal resolution in responding to shifts in target position that were faster than the lag (e.g., greater than about 4 per second), or it could reflect poorer spatial precision in matching target and cursor position. These possibilities might have been distinguishable had we included variations in the rate at which the target positions were changed, but unfortunately this type of manipulation was not incorporated in the present study. Another factor that could be contributing to the larger residual error is greater variability in response lag throughout the trial, so that the adjustment for the average lag only partially compensated for the actual lag, which varied across time.

The research strategy described by Salthouse (2001b) has now been applied to the assessment of inhibition, task-switching, and time-sharing aspects of executive functioning. In each case, a distinct executive functioning construct could be identified, but the constructs were quite narrow because the relevant variables were derived from very similar types of tasks. The approach of beginning with narrow or specific constructs is valuable to determine whether a coherent construct can be identified under what might be considered the most favorable conditions and, if so, to evaluate its relations to age and to other types of cognitive functioning. However, at least three directions could be pursued in future research. One possible direction is to extend the strategy to investigate other hypothesized aspects of executive functioning, such as planning or updating. A second direction is to expand the range of tasks presumed to assess the relevant aspect of executive functioning in an attempt to identify a broader construct. In the case of time sharing, this might involve examining different combinations of primary and secondary tasks to determine whether the correlations are large enough to justify the assumption of a unitary time-sharing construct. A third direction for future research is to examine several hypothesized aspects of executive functioning simultaneously. This would allow the structure of a higher-order executive functioning construct to be determined, in addition to its relations to age and to other measures of cognitive functioning. Weak correlations in prior studies among variables from neuropsychological tests often postulated to assess executive functioning made the possibility of a unitary executive processes construct unlikely, but greater success in establishing the existence, and determining the structure, of an executive processes construct might be expected after research such as that described in the present study has established the existence of coherent constructs representing different hypothesized aspects of executive functioning. Furthermore, even if little or no unique relations to other measures of cognitive functioning were evident with constructs reflecting specific aspects of executive functioning, moderate to strong relations might be apparent with a broader executive functioning construct that represents what is common to those lower-order constructs.

In summary, adult-age differences in time-sharing aspects of executive processes were investigated with a strategy recently described by Salthouse (2001b). The major advantages of the strategy are as follows: (1) It focuses on theoretical constructs rather than on individual variables that almost certainly do not fully represent the construct, and likely also reflect aspects irrelevant to the construct; and (2) it examines the relation of the construct both to age and to other aspects of cognitive functioning while taking into consideration other possible influences. Significant correlations among the time-sharing costs across three different primary tasks, together with small correlations with other types of variables, provided evidence for a unitary time-sharing construct. However, results of this study provide only moderate support for hypotheses concerning the role of executive functioning in adult-age differences in cognition because the relations of the construct to age and to other measures of cognitive functioning were weak relative to those associated with a construct of perceptual speed.

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NOTES

1. Perhaps the ideal method to deal with this problem involves the generation of complete attention-operating functions by varying the emphasis on each task across conditions, and then deriving an index of time-sharing ability based on the area above the function (Somberg & Salthouse, 1982). However, this is seldom practical because many trials are required in each of several task emphasis conditions and thus attention-operating functions are very time-consuming to generate.

2. A very similar pattern of results was obtained in a nearly identical study involving 54 adults between 21 and 81 years of age. All of the same tasks were administered except that the three primary tasks in that study were a verbal fluency task, a continuous arithmetic task, and the same paired-associates task used in this study. A two-group structural equation model comparing the two studies revealed that all of the path coefficients in the two samples could be constrained to be identical without a significant loss of fit, except those between the time-sharing construct and the three time-sharing costs.

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