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Changes in Executive Control Across the Life Span: Examination of Task-Switching Performance

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A study was conducted to examine changes in executive control processes over the life span. More specifically, changes in processes responsible for preparation and interference control that underlie the ability to flexibly alternate between two different tasks were examined. Individuals (N = 152) ranging in age from 7 to 82 years participated in the study. A U-shaped function was obtained for switch costs (i.e., the time required to switch between tasks compared with a repeated-task baseline), with larger costs found for young children and older adults. Switch costs were reduced with practice, particularly for children. All age groups benefited from increased preparation time, with larger benefits observed for children and older adults. Adults benefited to a greater extent than children when the interval between the response to one task and the cue indicating which task to perform next was lengthened, which suggested faster decay of interference from the old task set for adults than for children. A series of hierarchical analyses indicated that the age-related variance in task-switching performance is independent, at least in part, from the age-related variance in other cognitive processes such as perceptual speed and working memory. The results are discussed in terms of the development and decline of executive control processes across the life span.

Mental development has been viewed as progressing in the shape of an inverted U (Belmont, 1996; Vygotsky, 1934/1962). Changes have been viewed as a shift from stimulus-driven behavior in childhood to internally controlled behavior during young and middle adulthood back to stimulus-driven behavior during older adulthood (Belmont, 1996). Empirical studies have shown development and decline across the life span, from childhood to older adulthood, in several aspects of cognition, including processing speed (Kail & Salthouse, 1994), inhibitory control (Williams, Ponesse, Schachar, Logan, & Tannock, 1999), interference control (Comalli, Wapner, & Werner, 1962), and task coordination (Mayr, Kliegl, & Krampe, 1996).

In the present study, we examined changes in executive control processes across the life span. Executive control processes encompass those cognitive functions that are concerned with the selection, scheduling, and coordination of computational processes that are responsible for perception, memory, and action (Meyer & Kieras, 1997; Norman & Shallice, 1986; Shallice, 1994). More specifically, we used the task-switching paradigm to examine changes in selective aspects of executive control.

The task-switching paradigm involves the performance of two simple tasks such as deciding whether a letter is a vowel or a consonant or deciding whether a number is odd or even. In one condition (i.e., the nonswitch baseline or repetition condition), the same task is repeated a number of times. In a second condition (i.e., the switch or alternation condition), subjects switch from one task to the other. The switch and nonswitch trials can be presented either in a single block of trials (D. A. Allport, Styles, & Hsieh, 1994; Jersild, 1927) or in separate trial blocks (Gopher, 1996; Kramer, Hahn, & Gopher, 1999; Rogers & Monsell, 1995). The time required to complete the executive control processes necessary to switch from one task to another, such as the selection from long-term memory and the configuration in working memory of the appropriate processing algorithms and the inhibition of previously used processing algorithms, is inferred from the increased reaction time (RT) observed when a task switch occurs compared with when the same task is performed either separately or in a run of trials of the same task (i.e., switch cost RT = switch trial RT − nonswitch trial RT).

Theoretical Issues in Task Switching

There are two different classes of theories that attempt to explain performance decrements (i.e., switch costs) during changes in task set. One class of theories emphasizes the role of active preparation, whereas the other emphasizes passive interference. The preparation theories focus on the active preparation for task performance. These processes allow the individual to prepare in advance by reconfiguring his or her internal task state. In contrast, interference theories rely on passive decay of the previous task set from working memory.

Preparation Time

Cuing target stimuli in advance reduces the time needed to detect and classify these stimuli (Bertelson, 1967; Bertelson &

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Tisseyre, 1968, 1969; Davis & Taylor, 1967; Niemi & Näätänen, 1981; Sudevan & Taylor, 1987). Older adults and children are often able to prepare for task changes as well as young adults, although overall RT is slowed in children and older adults (Botwinick & Brinley, 1962; Hartley, Kieley, & Slabach, 1990; Hughes, Ratcliff, & Lehman, 1998). Introducing uncertainty into the timing of target presentation relative to the cue reduces the effectiveness of the cue (Bertelson & Boons, 1960; Näätänen, 1970; Näätänen & Merisalo, 1975). Providing time to prepare for task changes, by precuing task changes, reduces switch costs (Kramer et al., 1999; Meiran, 1996, 2000; Rogers & Monsell, 1995).

Rogers and Monsell (1995) distinguished between two types of preparation: exogenous, or stimulus-triggered, preparation and endogenous, or active, preparation. Endogenous preparation is under the intentional control of the subject, whereas exogenous preparation occurs in response to presentation of the task cue. Exogenous preparation occurs automatically in response to imperative stimulus presentation. Either of these forms of preparation could explain the benefit of advanced task cuing, at least after practice in shifting among a set of tasks. De Jong (2000) has argued that residual switch costs can be accounted for by a failure to prepare on a subset of trials.

Task Set Inertia

Allport has argued that performance costs observed when individuals switch between tasks are the result of decreased interference, over time, from the preceding task set, as a result of decay of the previous task set in working memory (A. Allport & Wylie, 1999, 2000; D. A. Allport et al., 1994; Hsieh & Allport, 1994; see also Mayr & Keele, 2000), rather than the failure to fully prepare for the subsequent task. Providing additional time between a subject's response and the next stimulus results in switch cost reduction and supports the task set inertia (TSI) theory (D. A. Allport et al., 1994). However, the results obtained by several investigators suggest a potential problem with TSI theory as a complete account for switch costs.

For example, Meiran (1996) systematically and orthogonally manipulated two different time periods between a subject's response and the subsequent stimulus. The response–cue interval (RCI) is the time between a subject's response and the cue that indicates which task will be performed next. The cue–target interval (CTI) is the amount of time between the cue indicating the task to be performed next and the stimulus for that task. Meiran (1996) reasoned that varying the RCI while holding the CTI constant would provide a measure of the decay of TSI because subjects would not know which task to prepare for next until they received the cue. Alternatively, varying the CTI while holding the time between the subject's response and the task stimulus (response–stimulus interval, or RSI) constant would allow for an assessment of the ability of a subject to actively prepare for the next task. Meiran's (1996) results (see also Meiran, Gotler, & Perlman, 2001) indicated that switch costs were reduced when both of these intervals were manipulated, which suggested a role for both active preparation and TSI decay in switching between tasks.

Life Span Changes in Executive Control Involving Set Shifting

Most age-related studies of executive control in changing task set have, to date, focused on children and young adults or on young and older adults. The Wisconsin Card Sorting Test (WCST) (Anderson, Damasio, Jones, & Tranel, 1991; Berg, 1948; Heaton, Chelune, Talley, Kay, & Curtiss, 1993) has provided the main paradigm used to examine changes in executive control involved in switching tasks or stimulus sets from childhood to young adulthood and across the adult years. In the WCST paradigm, subjects are required to sort cards into different piles on the basis of the number, shape, and color of geometric objects that are printed on the cards. Subjects are required to discover the sorting rule on the basis of feedback provided by the tester. Following 10 correct sorts, the sorting rule is changed without warning and subjects must again discover the new sorting rule on the basis of tester feedback. Performance on the WCST, particularly measures of perseverative errors, has been found to be associated with frontal lobe lesions in human patients (Drewe, 1974; Heaton et al., 1993; Milner, 1963) and with activation of the dorsolateral prefrontal cortex (Berman et al., 1995).

A number of studies have found that performance on the WCST, including decreased errors, perseverative responses, perseverative errors, nonperseverative errors, failures to maintain task set, and number of trials needed to complete first category, improves from approximately 6 to 20 years of age, with the largest improvement occurring between 6 and 10 years of age (Chelune & Baer, 1986; Heaton et al., 1993; Paniak, Miller, Murphy, Patterson, & Keizer, 1996; Rosselli & Ardila, 1993). With regard to aging, a number of investigators have found performance declines beginning in the early 60s (Botwinick, Robbin, & Brinley, 1960; Heaton et al., 1993; Robbins et al., 1998).

Although the results obtained with the WCST have provided many important insights into changes in executive control across the life span, we believe that the task-switching paradigm also has much to offer with regard to studying task coordination. For example, although the WCST is a complex task that requires not only problem solving and efficient working memory to discover the new rule after a change but also the ability to inhibit inappropriate responses, the task-switching paradigm entails the use of well-learned and well-specified rules. Therefore, the task-switching paradigm enables one to focus on the process of switching task sets in the absence of problem solving. Second, although the WCST is traditionally administered as an untimed task, task switching entails the recording of both response speed and accuracy, thereby enabling the assessment of potential speed–accuracy trade-offs within and across age groups. Third, the task-switching paradigm includes a baseline (i.e., the nonswitch trials) against which switch performance can be compared. Finally, as described above, experimental manipulations in the task-switching paradigm enable the dissociation of different mechanisms (i.e., active preparatory processes and TSI) that support task-switching performance. Therefore, on the basis of these considerations, we believe that task switching can provide a valuable tool with which to examine life span changes in selective aspects of executive control.

The Present Study

Our main goal in the present study was to examine changes, across the life span, in the ability to switch between different tasks. Such a skill is pervasive in many everyday activities such as automobile driving, in sporting activities, and in school and workplace functions and is therefore important from both theoretical and applied perspectives.

It is also the case that the skill of task switching relies, as suggested above, on the processes of preparation and inhibition of inappropriate task sets, that is, those processes that fall under the umbrella of executive control. Such processes are supported, in large part, by frontal and prefrontal regions of the brain. Indeed, recent functional magnetic resonance imaging (fMRI) and human lesion studies have confirmed that these brain regions are utilized during task switching (DiGirolamo et al., 2000; Dove, Pollman, Schubert, Wiggins, & von Cramon, 2000; Keele & Rafal, 2000; Kimberg, Aguirre, & D'Esposito, 2000).

Given the central role played by frontal and prefrontal regions of the brain in task switching as well as the evidence for continued development of frontal lobe function well into adolescence and the waning of frontal lobe efficiency as a function of normal aging (Krasnegor, Reid, & Goldman-Rakic, 1997; Stuss, 1992; West, 1996), we expected that the task-switching paradigm would provide a sensitive metric of life span changes in selective aspects of executive control, particularly with regard to preparatory and inhibitory processes.

In our study, subjects performed two different tasks: deciding whether the number 1 or the number 3 was presented on the computer screen and deciding whether a single number or three numbers were presented on the screen. Subjects either performed these tasks repeatedly (in nonswitch blocks or in runs of trials in switch blocks) or switched from one task to the other. The main dependent variable was the extra time required to perform a task after having performed the other task, as compared to the time required to complete the same task when it was performed repeatedly (i.e., switch cost RT = switch trial RT − nonswitch trial RT).

We examined the contribution of two different processes that potentially contribute to switch costs by orthogonally manipulating the RCI and the CTI (see D. A. Allport et al., 1994; Cepeda, Cepeda, & Kramer, 2000; Kramer et al., 1999; Meiran, 1996; Rogers & Monsell, 1995). Reductions in switch cost with increasing RCI can be interpreted in terms of decay of TSI, whereas reductions in switch costs with increasing CTI suggest preparatory benefits (i.e., benefits attributed to the preparation of the task set for the task to be performed next).

Evidence for age-related differences in both preparatory processes and TSI has been reported in studies of young and old adults (Kramer et al., 1999; Mayr & Liebscher, 1996; Meiran et al., 2001). However, because these studies compared a single young adult group and a single old adult group, they did not enable an assessment of the shape of the function relating age to changes in these processes. In addition, to our knowledge, there have been no studies that have examined the development of these processes from childhood to young adulthood. In our study, we included 152 subjects ranging in age from 7 to 82 years in order to examine the development and decline of executive processes underlying task switching.

Given the sensitivity of the task-switching paradigm to frontal lobe function and the reduced efficiency of frontal lobe function in children and older adults, we predicted improvement in the use of longer CTIs (i.e., preparatory processes) from childhood to young adulthood and decreased efficiency in the use of extra time to prepare among older adults. A similar pattern of effects was expected for longer RCIs (i.e., TSI). However, although we expected young children and older adults to be able to capitalize on additional practice with longer CTIs, to reduce switch costs attributable to a lack of sufficient preparation (Kramer et al., 1999), we did not expect practice to influence switch cost differences between the short and long RCIs. This follows from the assumption that TSI represents a passive decay phenomenon (A. Allport & Wylie, 2000) and therefore should be relatively uninfluenced by practice.

Given children's and older adults' susceptibility to interference from task-irrelevant environmental information as well as the retrieval of task-irrelevant information from long-term memory into working memory (Bjorklund & Harnishfeger, 1990; Kramer et al., 1999; West, 1996), we expected that switch costs would be exacerbated, particularly for children and older adults, for incompatible stimulus–response mappings (i.e., when the currently relevant task calls for one response and the currently irrelevant task calls for a different response—see Figure 1).

Another important component of our study is the attempt to examine the contribution of other cognitive processes such as perceptual speed and working memory to age-related differences in task switching. In recent years, a good deal of research in the domain of cognitive aging (Cerella, 1985; Madden, Pierce, & Allen, 1992; Salthouse, 1996a, 1996b) and development (Kail, 1991, 1996; Kail & Salthouse, 1994) has suggested that a large proportion of the age-related variance in cognition in complex laboratory tasks can be accounted for by age-related differences in constructs such as perceptual speed and working memory (as measured by simple paper-and-pencil or computer-based tasks). Thus, another important goal of our study was to determine whether development and decline in task switching represent unique age-related variance, presumably related to executive control processes that entail preparation and resistance to interference

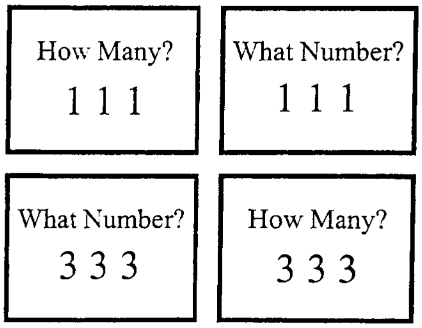

Figure 1. Example stimulus displays. The top stimulus displays represent response-incompatible trials, because the "3" key is pressed when the "How Many?" task is performed and the "1" key is pressed when the "What Number?" task is performed. The bottom stimulus displays represent response-compatible trials, because the "3" key is pressed regardless of which task is performed.

(TSI), or whether they can instead be accounted for by differences in perceptual speed and working memory among age groups. We addressed this issue through a series of hierarchical regressions with composite measures of perceptual speed and working memory as predictors and age-related variance in switch performance as the criterion measure.

Method

Subjects

Five groups of subjects, 152 in total, participated in the study. Age ranges for the groups were 7–9 years (young childhood), 10–12 years (middle childhood), 13–20 years (adolescence), 21–30 years (young adulthood), 31–40 years (young-middle adulthood), 41–50 years (middle adulthood), 51–60 years (middle-old adulthood), 61–70 years (old adulthood), and 71–82 years (older adulthood). Subjects who had experienced unconsciousness that was due to head trauma, who were taking beta-blockers or psychotropic medication, or who had been diagnosed with a mental illness or learning disability were excluded from the study. All subjects had normal or corrected-to-normal near and far vision (20/40 or better) as measured by Snellen acuity charts. No subject had participated previously in a task-switching experiment. Age groups were similar with respect to IQ score, education level, health, vision, handedness, and gender. Table 1 presents a summary of the demographic information, and Table 2 presents the relevant statistics on the demographic information.

Stimuli

Stimuli for the task-switching paradigm were presented at fixation. Each of the four possible stimuli consisted of either a single digit (1 or 3) or three digits (1 1 1 or 3 3 3). In other words, either one or three numerical ones or threes were presented. Above each target stimulus, either the words "What number?" or the words "How many?" appeared depending on which task was being performed on that trial. Examples of the stimulus displays are presented in Figure 1.

Apparatus

For the computerized portion of this experiment (i.e., the task-switching paradigm), Intel 486-based computers with 15-in. (38-cm) monitors were used. Subjects made responses using the numeric keypad attached to a standard 101-key keyboard.

Table 2
Results of Analyses of Variance on Demographic Variables

Variable	$F(8, 143)$	p
Sex	1.0	.440
Near vision	5.1	.000
Far vision	1.6	.120
Education	56.6	.000
Health	2.5	.014
K-BIT Verbal	2.3	.024
K-BIT Matrices	0.79	.613
K-BIT Composite	2.3	.023

Note. K-BIT = Kaufman Brief Intelligence Test.

Procedure

Subjects were tested in three experimental sessions over different days, completing all three sessions within a period of 1 week. In the first session, demographic data—including scores on the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 1990), health ratings, education, gender, near and far vision, and age—were collected. Measures of perceptual speed (Box Completion, Digit Copying, Digit–Symbol Substitution, and Letter Comparison) and working memory capacity (Wechsler Adult Intelligence Scale—Revised [WAIS-R] Backward Digit Span) were also collected during the first session, as was WAIS-R Forward Digit Span.

Perceptual speed tasks used paper-and-pencil measures (Salthouse, 1992). During Box Completion, a fourth side was added to three-sided boxes as quickly as possible. The number of boxes correctly completed within 30 s was counted. In Digit Copying, digits were successively copied into boxes below the digits as quickly as possible. The number correctly copied in 45 s was counted. In Digit–Symbol Substitution, symbols in a chart corresponding to each digit were successively copied into boxes below the digits as quickly as possible. The number of correct responses in 60 s was counted. In Letter Comparison, the number of letter string pairs correctly compared (by writing S for same or D for different) minus the number incorrectly compared was counted. Three different string lengths (3, 6, or 9 items) were compared, in separate 30-s periods. For Forward and Backward Digit Span, standard WAIS-R administration and scoring procedures were used.

The second and third sessions were identical and consisted of a computerized task-switching paradigm in which accuracy and RT measures were collected. Following the suggestion of Welsh and Pennington (1988), who found that executive control studies often use tasks that are too

Table 1
Demographic Information for Subjects

Age range (years)	n	Mean age (years)	Sex (% female)	Near vision (20/x)	Far vision (20/x)	Education (years)	Health[a]	K-BIT Verbal	K-BIT Matrices	K-BIT Composite
7–9	14	8.5	50	20	25	3.0	4.9	114	116	117
10–12	12	11.6	67	21	22	5.8	4.9	111	111	117
13–20	17	17.8	53	21	21	11.7	4.4	103	109	107
21–30	18	24.8	67	20	21	16.2	4.5	110	111	111
31–40	17	36.5	88	21	20	16.8	4.6	105	107	107
41–50	17	46.5	71	22	21	16.9	4.6	109	108	110
51–60	16	57.0	75	24	22	15.9	4.3	113	109	113
61–70	20	66.1	65	22	24	15.5	4.3	113	111	113
71–82	21	76.2	57	26	26	15.6	4.4	113	113	115

Note. K-BIT = Kaufman Brief Intelligence Test.
[a] 5 = excellent.

difficult for young children, we administered tasks appropriate for young children. This paradigm used task changes every one, two, or three trials. Two nonswitch blocks (50 trials each) and eight switch blocks (128 trials each) were collected during each session. The first nonswitch block required the subject to identify the number present on the screen (either the number 1 or the number 3) using the "1" and "3" keys on the numeric keypad. The second nonswitch block required identification of how many digits were present (either one digit or three digits). The words "What number?" (for the what-number task) or "How many?" (for the how-many task) preceded each numerical stimulus. Four different stimuli were used. Two of them were response compatible (1 and 3 3 3) because both tasks required the same keypress. The other two were response incompatible (1 1 1 and 3) because different keypresses were required for each task. The eight switch blocks required subjects to alternate between the what-number and how-many tasks. In each block, half the stimuli were response compatible and half were response incompatible.

Subjects were cued on each trial with the words "What Number?" or "How Many?" presented above the stimulus to which the subjects responded. After each response, a variable amount of time elapsed between the response and the cue (i.e., the RCI). We used this variation in the RCI to examine TSI, that is, the decay of a previously relevant task set. The cue was present for a variable amount of time before the numerical stimuli to which subjects responded appeared. This amount of time was the CTI, which we used to examine subjects' preparation of the subsequent task set. The RCI and CTI were varied orthogonally. Each combination of CTI (100 or 1,200 ms) and RCI (100 or 1,200 ms) was presented in a separate block of trials. Each combination of CTI and RCI was presented in two different blocks in each experimental session. The order in which the nonswitch and switch blocks were presented was counterbalanced between and within subjects.

Because of fatigue, 7–9-year-olds performed only four switch blocks per session. All eight blocks of 7–9-year-olds' data were combined and are presented in graphs and data tables as Session 2 (because 10–82-year-olds completed eight blocks in Session 2).

Results

Three sets of analyses were performed.[1] The first set of analyses examined the effects of preparation (via the CTI manipulation) and TSI (via the RCI manipulation) on switch cost. Two methods of computing preparation benefits were used. In addition, the effects of practice were examined. The second set of analyses examined effects of response interference. Changes in interference control with practice were also addressed. The third set of analyses examined the possible contributions of perceptual speed and working memory capacity to switch costs as well as age-related differences in switch costs.

Switch cost can be determined by using either nonswitch-only block trials as a baseline or nonswitch trials in switch blocks as a baseline. Because there are advantages and disadvantages for each method of computing switch cost, we used both methods and compared differences. We used a regression analysis to examine the role of arousal and other between-block factors that might have been confounded with switch cost when a nonswitch block was used as a baseline.

Preparation and Task Set Inertia

Median RTs for each combination of RCI (100- or 1,200-ms RCI, which examines TSI), CTI (100- or 1,200-ms CTI, which examines preparation), trial type (nonswitch trial in the nonswitch-only block; switch trial in the switch block; first nonswitch trial after a switch trial; and second nonswitch trial after a switch trial), and practice (Session 2 or Session 3) were determined for each subject. Means of these median RTs were computed for each age group (7–9-year-olds, 10–12-year-olds, 13–20-year-olds, 21–30-year-olds, 31–40-year-olds, 41–50-year-olds, 51–60-year-olds, 61–70-year-olds, 71–82-year-olds) for each condition. The RT data are presented in Table 3.

Switch cost can be determined in two different ways. One method is to subtract RTs on nonswitch trials in switch blocks from RTs on switch trials in switch blocks. The other method is to subtract RTs on nonswitch trials in nonswitch blocks from RTs on switch trials in switch blocks. The benefit of the former method is that effects of arousal or other between-block factors (e.g., different performance strategies) are eliminated from the switch cost measure. However, the benefit of the second method is that it can accommodate slow decay of TSI that may carry over from one switch trial to the next in a within-block switch cost measure.

Median RTs were submitted to five-way analyses of variance (ANOVAs) with RCI (100 ms or 1,200 ms), CTI (100 ms or 1,200 ms), trial type (either comparing switch trials to nonswitch-block trials or comparing switch and nonswitch trials during switch blocks), and practice (Session 2 or Session 3) as within-subject factors and age group (10–12-year-olds, 13–20-year-olds, 21–30-year-olds, 31–40-year-olds, 41–50-year-olds, 51–60-year-olds, 61–70-year-olds, 71–82-year-olds) as a between-subjects factor. One ANOVA was performed with each method of computing switch cost: within switch blocks or between switch and nonswitch blocks (trial type manipulation; see Table 4).

Overall RTs were shortest for young adults and longest for children and older adults (age main effect): $F(7, 130) = 280.3, p < .01$ within switch blocks; $F(7, 130) = 68.5, p < .01$ between switch and nonswitch blocks (see Figure 2). A significant switch cost also was found (trial type main effect): $F(2, 260) = 70.5, p < .01$ within switch blocks; $F(1, 130) = 705.7, p < .01$ between switch and nonswitch blocks (see Figure 3). Switch cost was larger for children and older adults than for young adults (Trial Type × Age interaction): $F(14, 260) = 2.1, p < .01$, effect size = .72 within switch blocks; $F(7, 130) = 6.2, p < .01$, effect size = .97 between switch and nonswitch blocks.[2] Switch cost was reduced with practice (Trial Type × Practice interaction; see Table 4 and

[1] Given the significant difference among age groups in self-reported health (see Table 2), we reran the major analyses concerned with switching performance with self-reported health rating as a covariate. The addition of the health covariate did not change any of the main effects or interactions involving the switching variables (i.e., switch vs. nonswitch, CTI, RCI).

[2] Given previous research (Cerella, 1985; Kail, 1991, 1996; Kail & Salthouse, 1994; Madden et al., 1992; Salthouse, 1996a, 1996b) that has suggested that age-related effects in complex task performance can often be accounted for by general speedup (when comparing children with young adults) or general slowing (from young adulthood to old age), we conducted additional ANOVAs in order to take baseline differences in RT into account. We accomplished this by analyzing the relative switch costs (i.e., switch RT / nonswitch RT). Age effects (both main effects and interactions) that were significant for the mean RT measure remained significant for the relative RT measure. Thus, life span differences in switching between tasks cannot be accounted for, in their entirety, by linear slowing models. The issue of the independence of switch processes from nonswitch processes is also addressed in the Results in the subsection entitled *Perceptual Speed and Working Memory Performance.*

Table 3
Mean Reaction Times (in Milliseconds) by Age, Practice, Trial Type, Response–Cue Interval (RCI), and Cue–Target Interval (CTI)

	Session 2				Session 3			
Age (years)	NSNS	SWSW	NS1SW	NS2SW	NSNS	SWSW	NS1SW	NS2SW
				100-ms RCI, 100-ms CTI				
7–9	893 (67)	1,670 (40)	1,517 (50)	1,438 (50)	—	—	—	—
10–12	714 (26)	1,398 (46)	1,309 (41)	1,333 (43)	683 (67)	1,159 (24)	1,080 (28)	1,025 (32)
13–20	551 (25)	1,043 (22)	980 (23)	931 (27)	557 (39)	961 (29)	888 (29)	855 (27)
21–30	453 (17)	839 (19)	790 (16)	761 (17)	461 (38)	732 (22)	665 (16)	658 (19)
31–40	542 (19)	954 (17)	940 (15)	906 (11)	562 (27)	848 (12)	823 (11)	792 (16)
41–50	653 (47)	1,115 (24)	1,085 (23)	1,081 (23)	775 (72)	1,174 (31)	1,147 (21)	1,096 (30)
51–60	557 (24)	1,099 (11)	1,104 (9)	1,078 (25)	674 (34)	981 (17)	987 (23)	950 (29)
61–70	629 (36)	1,181 (17)	1,167 (22)	1,115 (30)	737 (51)	1,096 (8)	1,072 (15)	1,036 (14)
71–82	709 (29)	1,387 (14)	1,367 (19)	1,321 (23)	838 (53)	1,260 (17)	1,243 (19)	1,221 (24)
				100-ms RCI, 1,200-ms CTI				
7–9	864 (49)	1,348 (45)	1,217 (33)	1,167 (67)	—	—	—	—
10–12	654 (35)	971 (48)	958 (44)	989 (80)	672 (66)	811 (19)	808 (21)	785 (47)
13–20	492 (22)	732 (19)	704 (22)	677 (19)	519 (40)	655 (18)	607 (16)	615 (18)
21–30	414 (12)	505 (8)	506 (14)	514 (26)	410 (21)	469 (10)	463 (9)	482 (18)
31–40	499 (14)	641 (13)	617 (15)	625 (29)	481 (18)	571 (8)	567 (18)	554 (13)
41–50	595 (40)	903 (28)	888 (14)	881 (18)	676 (59)	844 (18)	847 (22)	813 (20)
51–60	518 (20)	749 (25)	707 (14)	701 (13)	552 (27)	649 (21)	632 (17)	634 (23)
61–70	570 (28)	821 (16)	891 (30)	849 (27)	622 (35)	734 (13)	789 (14)	759 (13)
71–82	613 (24)	927 (20)	1,006 (24)	935 (25)	664 (38)	822 (25)	843 (18)	808 (14)
				1,200-ms RCI, 100-ms CTI				
7–9	865 (44)	1,994 (43)	1,917 (47)	1,832 (50)	—	—	—	—
10–12	682 (32)	1,384 (30)	1,334 (26)	1,280 (30)	732 (53)	1,094 (26)	1,077 (25)	1,070 (38)
13–20	519 (25)	1,056 (28)	988 (16)	946 (22)	579 (42)	933 (21)	890 (15)	899 (17)
21–30	437 (11)	724 (12)	713 (16)	697 (12)	478 (41)	660 (13)	638 (13)	622 (10)
31–40	487 (11)	821 (12)	806 (10)	777 (13)	552 (21)	746 (13)	726 (11)	720 (10)
41–50	592 (38)	1,053 (17)	1,030 (15)	997 (23)	777 (75)	1,090 (18)	1,048 (19)	1,005 (23)
51–60	498 (14)	922 (12)	901 (14)	900 (14)	643 (46)	834 (13)	811 (10)	815 (21)
61–70	574 (31)	1,059 (18)	1,046 (19)	989 (17)	700 (43)	965 (13)	931 (12)	902 (13)
71–82	629 (31)	1,252 (15)	1,192 (14)	1,163 (20)	758 (49)	1,150 (18)	1,096 (18)	1,090 (24)
				1,200-ms RCI, 1,200-ms CTI				
7–9	786 (44)	1,517 (53)	1,488 (48)	1,447 (58)	—	—	—	—
10–12	620 (37)	1,070 (48)	1,042 (53)	1,015 (44)	613 (42)	866 (20)	858 (18)	852 (24)
13–20	499 (24)	783 (24)	774 (21)	746 (23)	504 (35)	705 (27)	687 (22)	666 (22)
21–30	417 (13)	524 (24)	524 (21)	533 (25)	405 (25)	490 (17)	496 (16)	489 (16)
31–40	483 (10)	615 (13)	592 (15)	584 (14)	463 (15)	569 (11)	561 (10)	541 (9)
41–50	600 (42)	855 (17)	832 (16)	842 (24)	633 (46)	855 (25)	841 (23)	858 (36)
51–60	498 (17)	678 (18)	657 (11)	651 (13)	531 (23)	601 (16)	590 (11)	595 (10)
61–70	571 (22)	735 (15)	716 (13)	697 (10)	615 (36)	679 (9)	692 (8)	696 (12)
71–82	605 (22)	868 (11)	828 (13)	807 (18)	662 (42)	803 (18)	801 (14)	777 (12)

Note. Standard errors are shown in parentheses. NSNS = nonswitch trial in the nonswitch-only block; SWSW = switch trial in the switch block; NS1SW = first nonswitch trial after a switch trial; NS2SW = second nonswitch trial after a switch trial. Because of a concern about fatigue, the 7–9-year-olds performed only one half the number of trials as the other age groups.

Figure 2), with the largest improvement occurring for the 10–12-year-olds.

Additional ANOVAs were performed in an attempt to decompose age-related changes in switch cost.[3] Without these additional analyses, it would have been difficult to interpret interactions involving age. A separate ANOVA was performed for each age group that included trial type (either comparing switch trials with nonswitch block trials or comparing switch and nonswitch trials during switch blocks), RCI (100 or 1,200 ms), CTI (100 or 1,200 ms) and practice (Session 2 or Session 3). The results of these ANOVAs are discussed in the following sections when it is necessary to interpret age-related changes in switch cost.

Assessment of preparatory efficiency. By examining the effects of short versus long CTIs, we can address the effectiveness

[3] Because of space constraints, it was not possible to include the results of these ANOVAs, in their entirety, in this article. However, the results of the separate age group ANOVAs can be obtained from the authors upon request.

Table 4
Analysis of Variance Results for Reaction Times by Age, Response–Cue Interval (RCI), Cue–Target Interval (CTI), Trial Type, and Practice

	Nonswitch block trials vs. switch trials in switch block			Switch vs. nonswitch trials in switch block		
Variable	*F*	*df*	*p*	*F*	*df*	*p*
Age	68.5	7, 130	.000*	280.0	7, 130	.000*
RCI	93.4	1, 130	.000*	70.8	1, 130	.000*
RCI × Age	8.2	7, 130	.000*	12.3	7, 130	.000*
CTI	1,613.0	1, 130	.000*	190.0	1, 130	.000*
CTI × Age	9.1	7, 130	.000*	10.9	7, 130	.000*
Trial Type	705.7	1, 130	.000*	70.5	2, 260	.000*
Trial Type × Age	6.2	7, 130	.000*	2.1	14, 260	.010*
Practice	11.3	1, 130	.001*	257.0	1, 130	.000*
Practice × Age	7.2	7, 130	.000*	130.0	7, 130	.000*
RCI × CTI	61.0	1, 130	.000*	52.0	1, 130	.000*
RCI × CTI × Age	1.0	7, 130	.463	1.0	7, 130	.416
RCI × Trial Type	17.7	1, 130	.000*	0.8	2, 260	.449
RCI × Trial Type × Age	4.7	7, 130	.000*	1.9	14, 260	.027*
CTI × Trial Type	69.0	1, 130	.000*	37.0	2, 260	.000*
CTI × Trial Type × Age	4.0	7, 130	.001*	2.1	14, 260	.013*
RCI × CTI × Trial Type	37.5	1, 130	.000*	3.0	2, 260	.050
RCI × CTI × Trial Type × Age	2.5	7, 130	.021*	1.3	14, 260	.196
RCI × Practice	5.6	1, 130	.019*	9.8	1, 130	.002*
RCI × Practice × Age	0.8	7, 130	.601	1.1	7, 130	.354
CTI × Practice	7.2	1, 130	.008*	11.2	1, 130	.001*
CTI × Practice × Age	4.1	7, 130	.000*	3.2	7, 130	.004*
RCI × CTI × Practice	4.3	1, 130	.040*	1.4	1, 130	.239
RCI × CTI × Practice × Age	0.6	7, 130	.731	1.6	7, 130	.133
Trial Type × Practice	153.0	1, 130	.000*	0.8	2, 260	.449
Trial Type × Practice × Age	3.1	7, 130	.005*	0.8	14, 260	.693
RCI × Trial Type × Practice	0.3	1, 130	.592	4.1	2, 260	.018*
RCI × Trial Type × Practice × Age	1.4	7, 130	.203	1.3	14, 260	.231
CTI × Trial Type × Practice	46.6	1, 130	.000*	0.3	2, 260	.715
CTI × Trial Type × Practice × Age	0.9	7, 130	.506	0.8	14, 260	.709
RCI × CTI × Trial Type × Practice	11.0	1, 130	.001*	0.8	2, 260	.441
RCI × CTI × Trial Type × Practice × Age	1.3	7, 130	.264	0.6	14, 260	.867

Note. Results are shown for two methods of computing switch costs.
* Statistically significant.

with which subjects used the time to prepare for the subsequent task. Switch cost is much smaller when a long CTI is provided than when a short CTI is provided, using nonswitch trials from both switch blocks and nonswitch blocks as baselines (CTI × Trial Type interaction; see Figure 3 and Table 4). Children and older adults showed a greater reduction of switch cost with preparation than did middle-aged adults (i.e., CTI × Trial Type × Age interaction; effects sizes for between- and within-block comparisons were .88 and .70, respectively; see Figure 2 and Table 4). Separate ANOVAs for each age group showed a significant switch cost reduction for all age groups with increased preparation time when nonswitch-only block trials were used as a baseline (CTI × Trial Type interaction). Overall RTs were reduced when long preparation time was provided (main effect of CTI; see Figure 3 and Table 4), to a greater degree for children and older adults than for young adults (CTI × Age interaction; see Figure 2 and Table 4), who started out with faster overall RTs even when not prepared.

D. A. Allport et al. (1994) would argue that the performance benefit gained during the longer CTI may be due to decay of TSI rather than to active preparation. Because TSI decay may indeed take place during the CTI (Meiran, 1996; Meiran et al., 2001), we also need to examine preparation by comparing the 100-ms RCI, 1,200-ms CTI condition to the 1,200-ms RCI, 100-ms CTI condition. These conditions have equivalent time between tasks, so if TSI decay fully explains the benefit of increased CTI, there should be no difference between these conditions. Alternatively, improvements in performance could be attributed to subjects' taking advantage of the additional time to prepare for the subsequent task. As can be seen in Figure 3 (also see Table 5, CTI × Trial Type interaction), providing additional time to prepare (i.e., 1,200-ms CTI) led to a substantial decrease in switch cost, more so for children and older adults (CTI × Trial Type × Age interaction; see Figure 2 and Table 5). Therefore, a substantial portion of the switch cost appears to be attributable to the inability to prepare for a new task with a brief CTI.

Assessment of task set inertia. D. A. Allport et al. (1994; see also A. Allport & Wylie, 1999, 2000) have argued that TSI, which is a form of proactive interference from the previous task set, can explain most if not all of the performance cost observed when subjects must switch from one task to another. Within this theoretical context, the provision of additional time to allow for decay

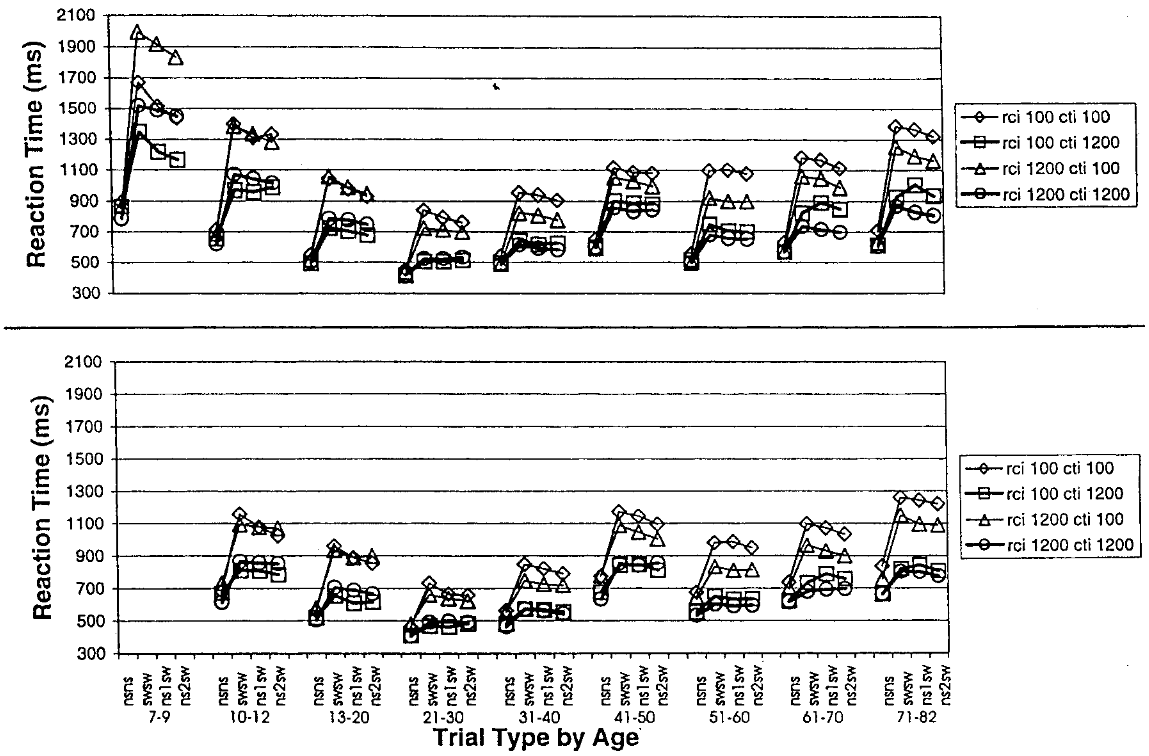

Figure 2. Reaction times by age group (in years), response–cue interval (rci; 100 or 1,200 ms), cue–target interval (cti; 100 or 1,200 ms), and trial type (nonswitch trial in nonswitch-only block [nsns]; switch trial in switch block [swsw]; first nonswitch trial after a switch trial [ns1sw]; and second nonswitch trial after a switch trial [ns2sw]). The data for Session 2 (first task-switching session) are presented in the top panel, and the data for Session 3 (second task-switching session) are presented in the bottom panel. Data for the 7–9-year-olds were available for only one session.

of TSI should result in a reduction in switch costs, particularly when nonswitch trial blocks serve as the baseline for the computation of switch costs. As indicated in Table 4 and Figure 3, switch costs did indeed decrease with increases in RCI (i.e., RCI × Trial Type interaction), consistent with the predictions of Allport's TSI account.

A significant three-way interaction among age, trial type, and RCI was also obtained for the between-blocks ANOVA (effect size = .92; see Table 4). With the exception of the 41–50-year-olds, adults of all ages showed a benefit from a longer RCI (significant RCI × Trial Type interactions for each age group). On the other hand, children failed to show a performance benefit. The younger children (7–9-year-olds) actually showed a cost for longer RCIs. This could have been due to the apparent difficulty that the younger children had waiting for trials with long delays.

Unlike in the between-blocks data (i.e., the calculation of switch costs by subtracting the switch trials from the nonswitch trials in the nonswitch blocks), we failed to find an RCI × Trial Type interaction within switch blocks (see Figure 3 and Table 4). This finding suggests that it may take more than two trials for TSI to decay. This interpretation is consistent with the results of Mayr and Liebscher (1998), who found that a substantial number of trials occurred before switch costs were reduced to baseline levels. Interestingly, a three-way interaction among trial type, age, and RCI (effect size = .65, see Table 4 and Figure 2) indicated that some benefit from the increased RCI was observed for the older adults.

Thus, for both the between-blocks and the within-block comparisons, adults were found to show greater benefits than children from increasing RCI delays. Such data suggest that TSI may decay more quickly for adults than for children.

Relationship Between Preparatory Efficiency and Task Set Inertia

As can be seen in Table 4 and Figure 3, significant three-way interactions were obtained, for both the between-blocks and within-block analyses, for the RCI × CTI × Trial Type interaction. Consistent with the results shown in Figure 3, the data suggest that performance benefits for longer RCIs were obtained only when CTIs were short (100 ms). Within the theoretical frameworks described above, this finding suggests that TSI becomes less of a factor when subjects have a sufficient amount of time to prepare for a new task.

Interestingly, this three-way interaction was less reliable for older adults with the between-blocks comparison. As can be seen

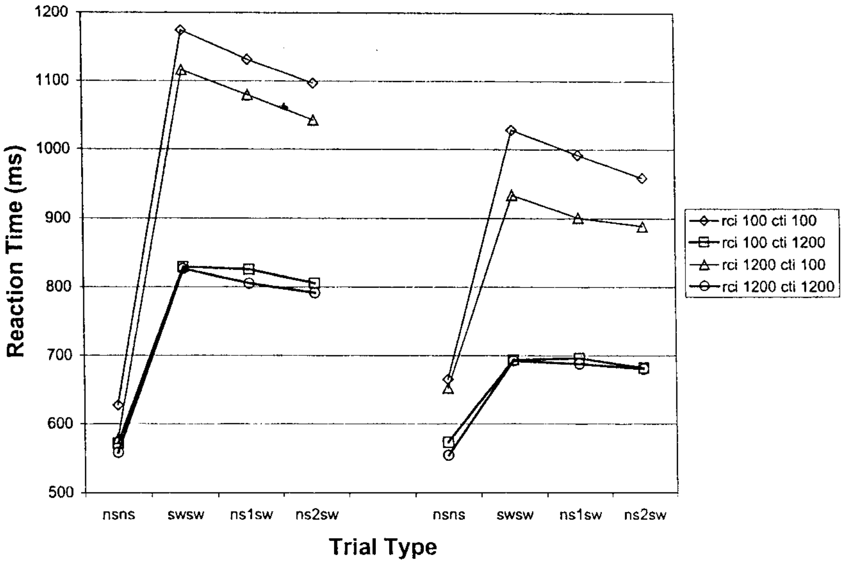

Figure 3. Reaction times by response–cue interval (rci; 100 or 1,200 ms), cue–target interval (cti; 100 or 1,200 ms), trial type (nonswitch trial in nonswitch-only block [nsns]; switch trial in switch block [swsw]; first nonswitch trial after a switch trial [ns1sw]; and second nonswitch trial after a switch trial [ns2sw]), and practice (Session 2 is shown on the left, and Session 3 is shown on the right).

in Figure 2, older adults showed benefits of increasing RCIs for both the short and long CTIs. These data suggest that increased preparation (i.e., via increased CTI) was not sufficient to fully overcome the effects of TSI for older adults.

Error Rate Analyses

False alarms (responses faster than 150 ms) were made in fewer than 2% of trials in all combinations of age and condition, and therefore we did not analyze them. Incorrect responses were submitted to an ANOVA with RCI (100 ms or 1,200 ms), CTI (100 ms or 1,200 ms), trial type (either comparing switch trials with nonswitch block trials or comparing switch and nonswitch trials during switch blocks), and practice (Session 2 or Session 3) as within-subject factors and age group (all age groups except 7–9-year-olds) as a between-subjects factor.

Error rates were quite low (<5.5%) across age groups and conditions. However, more errors were made when a switch occurred than when a task was repeated: $F(1, 130) = 210.6, p < .01$ and $F(2, 260) = 149.2, p < .01$ for the between-blocks and within-block switch cost comparisons, respectively. Error rates were also higher for young children than for adults, $F(7, 130) = 9.5, p < .01$. No evidence of a speed–accuracy trade-off was observed in the data. That is, error rates and response speed covaried such that errors were lower when responses were fast.

Assessment of Response Interference

As illustrated in Figure 1, responses to the currently relevant task and the other task could be compatible or incompatible. In an attempt to examine the interaction of response compatibility with age and switching, we submitted RTs to an ANOVA with response compatibility (compatible or incompatible), trial type (either comparing switch trials with nonswitch block trials or comparing switch and nonswitch trials during switch blocks), and practice (Session 2 or Session 3) as within-subject factors and age group (all age groups except the 7–9-year-olds) as a between-subjects factor.

The mean RT data are presented in Figure 4. RTs were significantly longer for the incompatible trials than for the compatible trials: between switch and nonswitch blocks, $F(1, 30) = 57.5, p < .01$; within switch blocks, $F(1, 30) = 62.7, p < .01$. More important, compatibility interacted with trial type such that the cost of performing with incompatible responses was larger during a switch trial than a nonswitch trial: between switch and nonswitch blocks, $F(1, 130) = 45.3, p < .01$; within switch blocks, $F(2, 260) = 29.3, p < .01$. Furthermore, the compatibility effect amplified the switch cost to a larger extent for the children than for the adults, $F(1, 130) = 15.3, p < .01$, effect size = 1.07. Error rates were quite low overall and showed a main effect for compatibility, $F(1, 130) = 391.7, p < .01$, a Compatibility $\times$ Age interaction, $F(7, 130) = 9.7, p < .01$, and a Compatibility $\times$ Trial Type interaction, $F(1, 130) = 241.4, p < .01$. Errors were higher for incompatible than compatible trials. Younger children had a higher error rate than adults. The difference in error rates between compatible and incompatible trials was larger on the switch trials than on the nonswitch trials. Thus, the error rate data showed the same trend as the data obtained for RT.

Potential Arousal Differences Between Performance in Switch and Nonswitch Blocks

Allport and colleagues (A. Allport & Wylie, 1999; D. A. Allport et al., 1994) argued that nonswitch trial blocks should be used as a baseline against which to examine switch costs because TSI takes more than a few trials to decay to a baseline level. One potential problem in using a nonswitch block as a baseline is that

Table 5
Analysis of Variance Results for Reaction Times by Age, Cue–Target Interval (CTI), Trial Type, and Practice

Variable	Nonswitch block trials vs. switch trials in switch block			Switch vs. nonswitch trials in switch block		
	F	*df*	*p*	*F*	*df*	*p*
Age	56.2	7, 130	.000*	570.0	7, 130	.000*
CTI	793.0	1, 130	.000*	762.0	1, 130	.000*
CTI × Age	6.4	7, 130	.000*	6.7	7, 130	.000*
Trial Type	635.0	1, 130	.000*	32.7	2, 260	.000*
Trial Type × Age	6.8	7, 130	.000*	2.2	14, 260	.008*
Practice	5.3	1, 130	.023*	681.0	1, 130	.000*
Practice × Age	5.4	7, 130	.000*	27.2	7, 130	.000*
CTI × Trial Type	434.0	1, 130	.000*	16.5	2, 260	.000*
CTI × Trial Type × Age	5.3	7, 130	.000*	2.3	14, 260	.006*
CTI × Practice	13.0	1, 130	.000*	0.1	1, 130	.723
CTI × Practice × Age	3.8	7, 130	.001*	2.3	7, 130	.033*
Trial Type × Practice	144.0	1, 130	.000*	1.1	2, 260	.333
Trial Type × Practice × Age	2.4	7, 130	.025*	0.7	14, 260	.770
CTI × Trial Type × Practice	31.6	1, 130	.000*	2.0	2, 260	.133
CTI × Trial Type × Practice × Age	0.9	7, 130	.546	1.2	14, 260	.302

Note. Results are shown for two methods of computing switch costs. CTI in this table has two levels and compares the 100-ms response–cue interval (RCI), 1,200-ms CTI condition with the 1,200-ms RCI, 100-ms CTI condition.
* Statistically significant.

arousal and other between-blocks factors (e.g., subject strategies) may be confounded with the level of TSI.

To address the potential effects of differential arousal between switch and nonswitch blocks, we computed correlations between switch cost residuals using nonswitch trials in nonswitch-only blocks (SSNN) and nonswitch trials in switch blocks (SSNS; see Figure 5). If these residuals were significantly correlated, it would be unlikely that differences between these two methods of computing switch cost would be due to arousal alone. Rather, significantly correlated residuals would indicate that a common executive control factor(s) exists between these two switch cost measures. Indeed, for both older and younger subjects, the residuals were significantly correlated (i.e., between SSNN and SSNS for the same tasks; see Figure 5), which argues against an arousal explanation for switch cost computed between blocks.

Residual correlation analyses also addressed commonalities in switch costs between tasks. When nonswitch-only block trials were used as a baseline, support for a common switch cost factor between tasks was found. However, when nonswitch trials in the switch block were used as the baseline for computing switch cost, a common switch cost factor between tasks was not found. This could be the result of reduced variance for these comparisons, because the switch costs were substantially larger when computed between blocks than when computed within blocks.

Perceptual Speed and Working Memory Performance

Perceptual speed and working memory performance increased during childhood and decreased during aging (see Table 6). Perceptual speed measures (Box Completion, Digit Copying, Digit–Symbol Substitution, and Letter Comparison) were slowest in young children, fastest in young adults, and intermediate for older adults. Working memory performance (Backward Digit Span) was lowest in young children, higher in young and middle-aged adults, and intermediate for older adults. Perceptual speed increased until around age 25 (see Figure 6) and then declined, whereas working memory performance (i.e., Backward Digit Span) improved until approximately age 60 (see Table 6) and then declined.

To examine the relationship between age and switch cost, independent of perceptual speed and working memory performance, we performed a series of hierarchical regression analyses, following Salthouse (1991). After examining the scatter plot of perceptual speed and switch trial RT data (see Figure 6), we decided to divide the data up into two age groups: 7–24-year-olds and 25–82-year-olds. This age division was created (a) to separate development from decline and (b) for consistency with the literature, which separates children and older adults (e.g., Williams et al., 1999). The results of the two hierarchical regressions are presented in Tables 7 and 8. For younger subjects, both perceptual speed and working memory reduced the effect of age on switch trial RT, as predicted by Salthouse (1991, 1996c). For older subjects, only perceptual speed reduced the effect of age on switch trial RT.

Most important, however, for both sets of analyses, a significant proportion of age-related variance in switch performance remained after the influence of perceptual speed, working memory, and nonswitch trial performance was factored out. Indeed, a parallel set of analyses that used switch cost (i.e., switch RT − nonswitch RT) rather than switch RT as the dependent variable produced a similar pattern of results. The age-related variance in switch costs remaining after all of the predictors in Tables 7 and 8 were entered into the hierarchical regression equation was 11% for the 7–24-year-olds and 50% for the 25–82-year-olds. Thus, these data strongly suggest that age-related improvement (from childhood to young adulthood) and decline in task-switching performance is, at least in part, independent of a variety of other information-processing

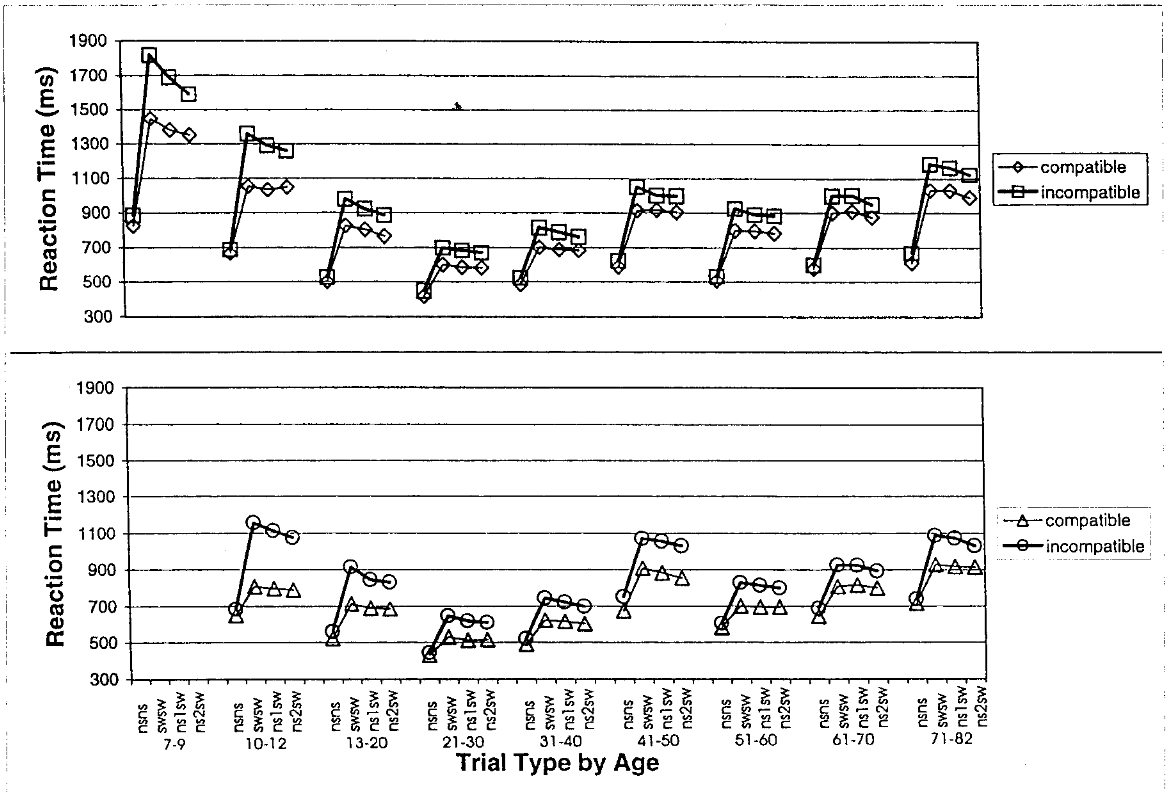

Figure 4. Reaction times by age group, response compatibility (compatible or incompatible), and trial type (nonswitch trial in nonswitch-only block [nsns]; switch trial in switch block [swsw]; first nonswitch trial after a switch trial [ns1sw]; and second nonswitch trial after a switch trial [ns2sw]). The data for Session 2 are presented in the top panel, and the data for Session 3 are presented in the bottom panel.

abilities. We submit that this unique aspect of task switching entails both the preparation for new tasks as well as the suppression of responses appropriate for previously performed tasks. In summary, our data provide evidence for a developmental time course of selective components of executive control.

Discussion

Our main goal in the present study was to examine changes in executive control processes across the life span and, in particular, the executive control processes that underlie the ability to switch

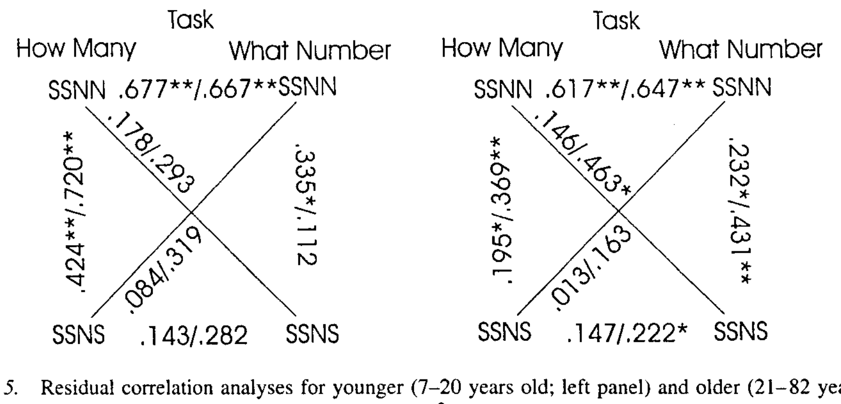

Figure 5. Residual correlation analyses for younger (7–20 years old; left panel) and older (21–82 years old; right panel) subjects. The first number in each pair is the R^2 value of the correlation for Session 2, and the second number is the R^2 value for Session 3. SSNN = regression of switch trials and nonswitch block trials; SSNS = regression of switch trials and nonswitch trials in switch block. *$p < .05$. **$p < .01$.

Table 6
Perceptual Speed (PS) and Working Memory Performance

Age range (years)	Backward Digit Span (no. correctly recalled)	Composite PS measure (Z scores)[a]	Box Completion (no. completed in 30 s)	Digit Copying (no. completed in 45 s)	Digit–Symbol Substitution (no. completed in 60 s)	Letter Comparison (no. completed in 30 s; correct − incorrect)		
						3 items	6 items	9 items
7–9	5.1	−1.40	29.8	34.9	20.8	9.6	5.7	3.8
10–12	5.8	−0.64	37.8	53.3	30.9	12.7	8.2	5.2
13–20	7.1	0.37	50.0	73.6	43.9	21.1	10.5	7.1
21–30	7.6	0.99	60.7	83.3	51.4	24.6	12.6	8.2
31–40	7.7	0.49	50.1	78.3	45.9	21.6	10.8	6.9
41–50	6.8	−0.03	47.5	67.9	37.5	17.3	8.4	6.0
51–60	8.9	0.37	53.6	77.4	41.6	17.8	9.9	6.9
61–70	7.2	−0.06	46.4	69.0	34.9	16.7	9.2	6.6
71–82	6.6	−0.44	40.3	65.0	31.1	13.0	6.6	5.7

Note. Significant age effects ($p < .001$) were found for all of the measures.
[a] Negative values reflect slow processing speed, and positive values represent fast processing speed.

between different tasks. An additional goal was the attribution of switch costs, the main dependent variable in the task-switching paradigm, to two potential underlying mechanisms, active preparation for a new task (De Jong, 2000; Rogers & Monsell, 1995) and decay of interference from a previously performed task (i.e., D. A. Allport et al.'s, 1994, TSI), and determination of the potential contributions of these processes to age-related differences in task-switching performance. Finally, we were interested in determining whether age-related differences in task-switching performance could be accounted for by age-related differences in other cognitive processes such as perceptual speed and working memory (Kail, 1996; Salthouse, 1996c).

With regard to the first goal, a U-shaped function was found for switch costs across the life span. That is, as illustrated in Figure 2, switch costs decreased from childhood to young adulthood, remained fairly constant across the adult years, and then began to increase after the age of 60. Interestingly, all age groups benefited from practice, with children and older adults showing the largest benefits. In addition, all age groups benefited from increased time to prepare for the subsequent task, that is, from increases in the CTI. These data are consistent with the proposal of Rogers and Monsell (1995; see also De Jong, 2000; Meiran, 1996; Salthouse, Fristoe, McGuthry, & Hambrick, 1998) that preparatory processes can be used to enhance task-switching performance. However, also consistent with the results of other studies was the fact that residual switch costs were observed for all age groups even when 1,200 ms were provided to prepare for the next task to be performed. Whether

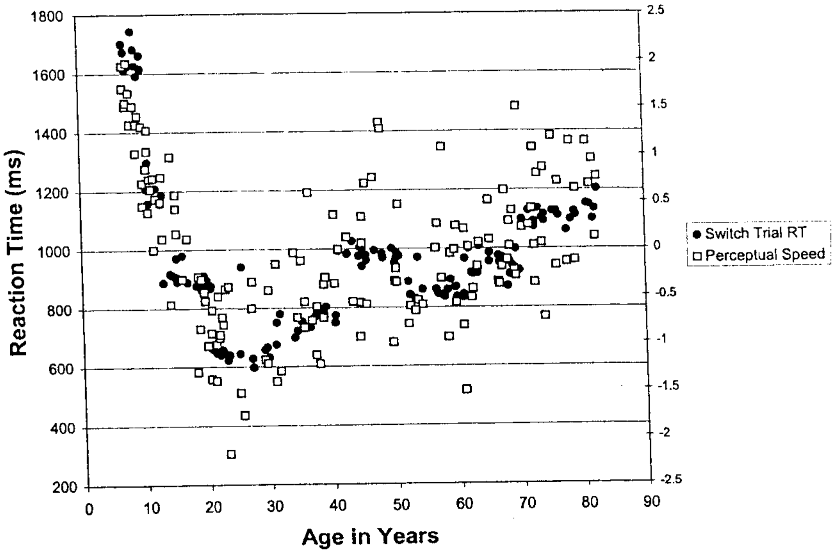

Figure 6. Scatter plot of switch trial reaction time (RT) and perceptual speed. Each data point represents an individual subject. The perceptual speed score for each subject was computed by averaging z scores from Box Completion, Digit Copying, Digit–Symbol Substitution, and Letter Comparison measures. Perceptual speed is displayed in terms of standard deviations from the mean, with positive values representing slower perceptual speed than the mean and negative values representing faster processing speed than the mean.

Table 7
Hierarchical Regression Analyses Predicting Switch Reaction Time (Dependent Variable) for Subjects 7 to 24 Years Old

Independent variable	R^2	R^2 change	F to enter	% of age effects not mediated by PS, WM, or NN
Age	.874*		353.5	
PS	.725*		134.3	
PS + Age	.874*	.149*	59.1	17
WM	.203*		13.0	
WM + Age	.876*	.674*	272.4	77
PS	.725*		134.3	
PS + WM	.726*	.001	0.3	
PS + WM + Age	.876*	.150*	59.5	17
NN	.676*		106.4	
NN + Age	.878*	.202*	83.1	23
PS	.725*		134.3	
PS + NN	.780*	.056*	12.7	
PS + NN + Age	.878*	.098*	39.5	11
PS	.725*		134.3	
PS + NN	.780*	.056*	12.7	
PS + NN + WM	.783*	.003	0.6	
PS + NN + WM + Age	.881*	.098*	39.6	11

Note. R^2 change is that associated with adding the variable to the regression equation. F evaluates statistical significance of the added variable. PS = perceptual speed; WM = working memory; NN = nonswitch trial reaction time.
* $p < .01$.

this residual switch cost is the result of failure to prepare on a subset of trials (De Jong, Berendsen, & Cools, 1999) or inherent limitations in endogenous preparatory mechanisms (Rogers & Monsell, 1995) is a topic for future research.

Evidence was also obtained for D. A. Allport et al.'s (1994; see also A. Allport & Wylie, 1999; Hsieh & Allport, 1994; see also Mayr & Keele, 2000) proposal that performance costs observed when individuals switch between tasks are the result of decreased interference, over time, from the preceding task set. Consistent with this TSI proposal, switch costs declined as the RCI was lengthened from 100 to 1,200 ms. Because subjects did not know which task would be performed next during the RCI interval, decreases in switch costs during this time can be attributed to a decay in interference from the previously performed task. Interestingly, with the exception of the 41–50-year-olds, performance benefits were observed for adults but not for children. Furthermore, as can be seen in Figure 3, the benefits of longer RCIs can mainly be attributed to the conditions in which the interval between the response and the subsequent stimulus was relatively short (i.e., with the 100-ms but not the 1,200-ms CTI). Thus, it appears that the deleterious effects of TSI can be overcome with sufficient preparation (i.e., a 1,200-ms CTI). Interestingly, however, this does not appear to be the case with older adults because, as illustrated in Figure 2, older adults showed significant benefits for longer RCIs at both short and long CTIs. Such a finding is consistent with the results of Mayr and Liebscher (1996), who reported data suggesting that older adults took longer to disengage from a previously performed task than did younger adults.

To summarize thus far, although children and older adults appear to show just as much (or more) benefit from increased preparation time as do young adults, children show little evidence for rapid decay of TSI, as evidenced by our failure to observe reliable effects of RCI for children. These data suggest a differential time course for the development of active preparatory processes and resistance to interference, with preparatory processes becoming efficient earlier in life. This conclusion is consistent with previous observations that children have difficulty resisting interference in paradigms such as the Stroop task (Comalli et al., 1962; Wise, Sutton, & Gibbons, 1975) and the stop-signal procedure (Williams et al., 1999). Our conclusion is also buttressed by the data illustrated in Figure 4, which indicate that children have more difficulty with incompatible response mappings (i.e., when the stimulus array primes one response for one task and the other response for the other task—see Figure 3) than do adults.

Another important goal of our study was to determine whether age-related differences in task switching are independent, in part, of age-related differences in other cognitive processes such as perceptual speed or working memory (Cerella, 1985; Kail, 1991, 1996; Kail & Salthouse, 1994; Madden et al., 1992; Salthouse, 1996a, 1996b). Kramer et al. (1999) demonstrated independence

Table 8
Hierarchical Regression Analyses Predicting Switch Reaction Time (Dependent Variable) for Subjects 25–82 Years Old

Independent variable	R^2	R^2 change	F to enter	% of age effects not mediated by PS, WM, or NN
Age	.674*		200.2	
PS	.293*		40.2	
PS + Age	.685*	.392*	119.7	58
WM	.027		2.7	
WM + Age	.680*	.653*	196.2	97
PS	.293*		40.2	
PS + WM	.293*	.000	0.0	
PS + WM + Age	.688*	.395*	120.5	59
NN	.192*		23.1	
NN + Age	.688*	.495*	152.1	74
PS	.293*		40.2	
PS + NN	.339*	.046	6.7	
PS + NN + Age	.693*	.354*	109.7	53
PS	.293*		40.2	
PS + NN	.339*	.046*	6.7	
PS + NN + WM	.339*	.000	0.0	
PS + NN + WM + Age	.696*	.357*	110.2	53

Note. R^2 change is that associated with adding the variable to the regression equation. F evaluates statistical significance of the added variable. PS = perceptual speed; WM = working memory; NN = nonswitch trial reaction time.
* $p < .01$.

between switch cost RTs and RTs for nonswitch trials when young and older adults were examined (see also Emerson, Miyake, & Shah, 1999; Rubinstein, Meyer, & Evans, in press; but see Salthouse et al., 1998). In the present study, we offered a more rigorous test of the independence hypothesis by including measures of perceptual speed and working memory in addition to nonswitch RTs and by including age groups ranging from 7 to 82 years.

As illustrated in Table 7, significant age-related variance in switch RTs remained after we removed age-related variance in perceptual speed, working memory, and nonswitch RT for 7–24-year-olds. However, it is also important to point out that subjects who responded quickly on a composite measure of perceptual speed (i.e., performance on the Box Completion, Digit Copying, Digit–Symbol Substitution, and Letter Comparison tasks) were also able to switch rapidly among the two different tasks in the task-switching paradigm. Table 8 illustrates the results of the hierarchical regressions for the 25–82-year-olds. As in the analyses of the younger subjects, significant age-related variance in switch RTs remained after we removed age-related variance in perceptual speed, working memory, and nonswitch RT. However, the proportion of age-related variance accounted for by perceptual speed, working memory, and nonswitch RT was substantially smaller for the older (i.e., 47%) than for the younger (89%) participants. Thus, these data appear to suggest that the executive control processes that underlie task-switching performance become more differentiated later in life. Interestingly, however, as with the analyses of the younger participants, older adults who performed quickly on the perceptual speed tests also showed reduced switch costs. Therefore, perceptual speed appears to be an important construct throughout the life span, albeit to a lesser extent for older adults than children.

In summary, the results of the hierarchical regressions, when viewed in conjunction with the assessment of switch costs and their interaction with the RCI and CTI factors, appear to suggest a differential time course for the development and decay of the executive control processes that underlie the ability to coordinate multiple tasks. For example, the manipulation of the RCI had a different impact on children and older adults, with older adults showing substantially more benefit from longer intervals than did children. These data may suggest that TSI takes significantly longer to decay in children than in adults. The results of the hierarchical regressions also suggest that the executive control processes that support task switching become more independent of perceptual speed and working memory abilities for older adults than for children.

However, other data obtained in the present study suggest a more similar time course for the development and decay of a subset of executive control processes that underlie task switching. For example, both children and older adults showed a substantial benefit from lengthened CTIs, indicating that both were able to capitalize on additional preparation to reduce switch costs. Furthermore, the results of the hierarchical regressions suggested that perceptual speed rather than working memory ability was the primary predictor of switch costs for both children and older adults.

Thus, it appears that although active preparatory processes appear to have a similar time course in development and decline, the more passive process(es) of TSI appear to play a different role in influencing task-coordination performance early and late in life. It is important for future studies to expand such observations beyond behavioral measures to include an examination of the brain circuits responsible for the development and decline of preparatory and TSI processes (DiGirolamo et al., 2000; Dove et al., 2000; Keele & Rafal, 2000; Kimberg et al., 2000).

Finally, it is important to acknowledge the limitations of a cross-sectional design as a means to examine life span differences in aspects of executive control such as those that underlie task-switching performance. As has been pointed out by Schaie (2000), cross-sectional designs are always potentially susceptible to cohort differences in uncontrolled variables that may influence the variables of interest. We made an effort to assess some of the factors that may have an impact on executive control (see Table 1) in an attempt to address potential uncontrolled cohort differences. However, additional research with longitudinal designs is certainly needed to confirm our findings.

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