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Age-related differences in reaction time task performance in young children

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Abstract

Performance of reaction time (RT) tasks was investigated in young children and adults to test the hypothesis that age-related differences in processing speed supersede a "global" mechanism and are a function of specific differences in task demands and processing requirements. The sample consisted of 54 4-year-olds, 53 5-year-olds, 59 6-year-olds, and 35 adults from Russia. Using the regression approach pioneered by Brinley and the transformation method proposed by Madden and colleagues and Ridderinkhoff and van der Molen, age-related differences in processing speed differed among RT tasks with varying demands. In particular, RTs differed between children and adults on tasks that required response suppression, discrimination of color or spatial orientation, reversal of contingencies of previously learned stimulus–response rules, and greater stimulus–response complexity. Relative costs of these RT task differences were larger than predicted by the global difference hypothesis except for response suppression. Among young children, age-related differences larger than predicted by the global difference hypothesis were evident when tasks required color or spatial orientation discrimination and stimulus–response rule complexity, but not for response suppression or reversal of stimulus–response contingencies. Process-specific, age-related differences in processing speed that support heterochronicity of brain development during childhood were revealed.

Keywords: processing speed, preschool children

Introduction

Age-related differences in processing speed have been observed on a variety of tasks, including verbal memory span, visual search, letter discrimination, memory search, retrieval fluency, mental addition, mental rotation, and response selection (e.g., Cowan et al., 1998; Hale, 1990; Kail, 1988; Ridderinkhof and van der Molen, 1997). In spite of this work, relatively little is known about the nature of development of processing speed in very young children. In the developmental literature, one account of the mechanism underlying age differences in processing speed is a general developmental mechanism (e.g., Cerella and Hale, 1994; Kail, 1993). This postulation was developed from results using a reaction time (RT) procedure pioneered by Brinley (1965) in the study of aging. The Brinley technique consists of plotting the obtained RT data of a particular age group against that of a group of young adults, either collapsing across conditions of a task or collapsing across tasks that vary in complexity. Use of this procedure, largely in school-age children, has revealed that the RT latencies of the child groups can be predicted accurately from those of young adults by simple mathematical equations (for a review, see Cerella & Hale, 1994). Specifically, mean RT during childhood at any specific age (RT_{child}) can be predicted from the young adults' mean RT (RT_{adult}) by multiplication of a "slowing" coefficient (m_{age}), $RT_{child} = m_{age}\ RT_{adult}$. The value of this "slowing" coefficient is simply a regression coefficient. Almost without exception, nearly all of the variance in the group means is accounted for by the simple regression equation, with R^2 typically exceeding .90 and often greater than .95 (for review, see Bashore & Smulders, 1995).

An early example of this approach in the developmental literature was provided by Hale (1990). She investigated RTs in 10-, 12-, and 15-year-olds and a group of young adults (19-year-olds) on four tasks: a choice RT task, a letter matching task, a mental rotation task, and an abstract matching task. For each child age group, eight mean latencies were calculated and then regressed against those of the young adult group. For each age group, the linear regression function accounted for more than 98% of the variance. The unstandardized slope of the regression function was progressively smaller across the child age groups in order of age; that is, the regression coefficient varied from 1.82 in 10-year-olds to 1.00 in 15-year-olds and young adults. Hale concluded that observed developmental differences in the processing speed were due to a general developmental mechanism. Unfortunately, Hale did not specifically examine whether task type influenced the age-dependent regression coefficients. Of interest, however, is the significant age by task type interactions that were noted for the letter matching and mental rotation tasks, providing some support for the presence of task-specific, age-related differences.

This phenomenon has been demonstrated to be robust even in very young children. Miller and Vernon (1997) investigated developmental differences in processing speed in 4- to 6-year-olds relative to adults using a battery of eight computer-administered tests. Adult RTs accounted for 90, 93, and 90% of the variability of RTs of 4-, 5-, and 6-year-old groups, respectively. Again, the regression coefficient decreased with age group, decreasing from 3.74 in 4-year-olds, to 3.20 in 5-year-olds, to 2.92 in 6-year-olds. These results were interpreted to support the global developmental mechanism even in very young children. Unfortunately, Miller and Vernon also did not investigate the influence of task type on the age-dependent regression coefficient. Miller and Vernon did, however, conduct a multivariate analysis of variance (MANOVA) to explore age differences based on the set of RT tasks. In the follow-up univariate analyses and post hoc comparisons, there were differences across pairs of age groups that varied somewhat across tasks, again providing some indirect support for task-specific, age-related differences.

Using both supplementary meta-analysis and experimental data, Kail (1993) concluded that developmental differences in processing speed are due to a global mechanism, although the nature of this mechanism remains to be elucidated. Kail speculated that one potential mechanism might relate to the information loss model (e.g., Dempster, 1993), where with advancing age children increasingly are able to better inhibit irrelevancy. More specifically, as children mature, they are better able to inhibit processing steps that are irrelevant to task performance. The net result is that less information is "lost" in irrelevant stimulus processing and more relevant information reaches the processing steps that are pertinent to task performance. As more information becomes available to the task-relevant processing steps, less time is needed for responding.

However, findings in elementary school children by Cowan et al. (1998) suggest that a global rate of processing is an oversimplication given that more specific rates also contribute to individual differences on span tasks. In that study, rates for rehearsal and retrieval independently were related to age and to span task performance and yet were independent of each other in latent variable models. Furthermore, several investigators (Bashore, 1994; Madden et al., 1992; Ridderinkhof and van der Molen, 1997) have demonstrated that the regression approach conceals process- or task-specific, age-related differences in processing speed. That is, even when there are local process- or task-specific developmental differences in performance, the use of regression analysis always will yield only a single regression equation across tasks or conditions, thereby erroneously supporting a global mechanism view.

The limitation of the regression approach has motivated the development of several alternative approaches (for a review, see Madden, 2001). In particular, Madden et al. (1992) developed a transformation method that retains the advantages of the regression approach but also incorporates process- or task-specific levels of analysis through the use of analysis of variance (ANOVA) methods. In this method, a Brinley plot function is calculated for the task condition means and then the RTs of the young groups are transformed by multiplication of the parameters derived from the best-fitting Brinley plot function. The new data, with both transformed RTs for younger groups and untransformed RTs for older adults, then are analyzed using ANOVA. Interactions of age group and task condition that remain significant following the transformation are considered to represent performance effects beyond those associated with generalized age-related slowing. In other words, the presence of any interactions after transformation reveals age-dependent, task-specific effects on processing speed that are not attributable to a global developmental mechanism. Using these methods with elementary school children grouped in three age groups and with adults, Ridderinkhof and van der Molen (1997) revealed significant differences in processing speed that were due to interactions between age group and task condition. These findings support the use of this transformation method to effectively reveal the process- or task-specific, age-related differences in processing speed.

Drawing from these findings in school-age children, it is unclear whether process- or task-specific, age-related differences will be observed in very young preschool children. There is substantial evidence that development of many cognitive processes in children under 6 years of age is not linear (e.g., Huttenlocher et al., 1991). Concomitantly, there is substantial brain development that occurs during this critical period, and Thatcher's work (1991, 1994, 1997) in electroencephalogram (EEG) signal coherence between local and long-distance brain areas suggests a qualitative shift in brain development that occurs between 3 and 6 years of age. Therefore, the pattern of findings observed in very young children might be different from that observed in school-age children. Although Miller and Vernon's (1997) findings with young children support the global developmental trend hypothesis, Madden and colleagues' (1992) analytic approach has not been used in this age range and might reveal task-specific, age-related differences in processing speed in these very young children.

The objective of this study, then, was to extend the use of the transformation method in very young children so as to assess whether such process- or task-specific, age-related differences in RT latency would be evident or whether a global, task-independent mechanism would better explain age-related differences in processing speed. To this end, age-related differences in performance among simple, discrimination, and choice RT tasks were examined in 4- to 6-year-olds and young adults using the approach proposed by Madden et al. (1992) and Ridderinkhof and van der Molen (1997). Specifically, age-related differences in processing speed were postulated beyond any global mechanism given the differences in task demands and processing requirements on the differing RT tasks.

Method

Participants

A total of 166 Russian-speaking children participated in this study. With permission from the school, children were recruited for participation from three kindergartens in Yekaterinburg (the capital of Ural region, Russian Federation). The sample consisted of 54 4-year-olds (M = 4.47 years, SD = 0.35, 26 boys and 28 girls), 53 5-year-olds (M = 5.62 years, SD = 0.41, 23 boys and 30 girls), and 59 6-year-olds (M = 6.52 years, SD = 0.37, 31 boys and 28 girls). A total of 142 (86%) of the participants were right-handed as assessed by Luria's assessment method of demonstrated hand preference on eight motor task trials. If a child conducted more than five trials with the right hand, he or she was considered as right-handed. All children in this study had normal birth histories and were free of medical, cognitive, language, sensory, and motor impairments according to their medical certificates. Children with suspected or known developmental or medical disorders that might affect task performance were excluded from participation. Demographic information (e.g., socioeconomic status) was not collected systematically, although children appeared to come from a variety of ethnic and socioeconomic backgrounds.

A total of 35 adult university students and staff members from Ural State University (17 men and 18 women) also participated in this study. Adult participants were between 19 and 35 years of age (M = 25.3 years, SD = 4.8).

Procedure

Testing was completed in one session lasting approximately 15 to 20 min. The RT tasks were administered in the same order for all participants because the interest here was individual differences in performance due to age and task interactions. In very young children, there often are idiosyncratic order effects; therefore, a fixed order is preferred (Carlson & Moses, 2001). A fixed order does not preclude order effects but rather renders the order effect constant across children of varying ages. RT tasks were presented on an IBM laptop computer with a 12-inch color monitor, with latency recorded by the computer in milliseconds. Each participant was positioned in front of the computer so that his or her eyes were approximately 40 cm from the screen, with hands positioned on the relevant key to respond to stimuli for each task using the standard keyboard of the IBM laptop.

All RT tasks required no reading ability. The time interval between key press and the appearance of the next stimulus varied randomly between 500 and 2000 ms to prevent anticipatory responding. During the trials, feedback was provided via a computer tone. Feedback was provided to facilitate task attention and perseverance in the youngest participants. The test stimuli consisted of pictures of different animals, all of which were approximately 3 inches in diameter.

The test battery consisted of three types of RT tasks: simple, discrimination, and choice. Within the latter two RT task types, there were three conditions within each task type.

Simple RT task

Here participants were required to press the space bar key with the dominant hand as soon as the stimulus picture of a common bee appeared on the screen. Participants were told in Russian, "Look! You see a bee. It will appear on the screen. You push the key as quickly as possible as soon as the bee appears." Following administration of five practice trials, participants completed 10 experimental trials. In this very simple condition, 10 trials (rather than 20 trials) were administered to facilitate continued interest in these young children. In pilot testing, several children indicated that the 20-trial version of the simple RT task was boring, and the standard deviation for the RTs was larger than expected. Given task simplicity, 10 trials were adequate to yield stable estimates of performance.

Discrimination RT task

On this task, participants pressed the space bar key with the dominant hand only for one of two stimuli that appeared on the screen. Participants were instructed to respond as quickly as possible while also maintaining response accuracy. There were three conditions within the discrimination RT task, with each condition using a different stimulus type: object identity, color, or spatial orientation. The general instructions and procedures were the same in all three conditions, but the type of discriminative stimulus differed. In the object discrimination condition (ODR), the target stimulus was a tiger and the nontarget was an elephant. The target and nontarget stimuli in the color discrimination condition (CDR) were green and yellow butterflies, respectively. In the spatial orientation discrimination condition (SDR), a rabbit in the usual presentation and in the mirror image were used as the target and nontarget stimuli, respectively. For each discrimination RT task condition, participants were instructed, "Look! You see a [target] and a [nontarget]. They will appear on the center of screen, sometimes a [target], sometimes a [nontarget]. Press this key as soon as you can only when the [target] appears. If you make a mistake, the computer will make this noise. You must press the button as quickly as possible, but try to make as few mistakes as you can." Following five practice trials (of object discrimination) to acclimate participants to the choice RT paradigm, participants completed 20 experimental trials (randomized presentation of 10 target and 10 nontarget stimuli) for each condition (object discrimination, color discrimination, and spatial orientation discrimination). The condition type was presented blocked, with a fixed order across participants (object discrimination, color discrimination, and then spatial orientation discrimination) again to minimize any idiosyncratic order effects in the youngest participants.

Choice RT task

In the choice RT task conditions, participants needed to press a computer key to all stimuli; however, a different key was required to be pressed to different discriminative stimuli. In this task, there were some memory demands in that participants were required to remember the particular response keys given that the keyboard keys were not colored or labeled with pictures. Accuracy was high, however, suggesting that there was little indication of memory of the response keys impairing performance. There were three conditions: two-choice (CR2), two-choice reversal (CRR), and four-choice (CR4). For both two-choice conditions, the left and right "Shift" keys were used, with the discriminative stimuli being a cat and a piglet. In the four-choice condition, the "X" and "<" keys also were used in response to stimulus pictures of a lion, a rabbit, a bird, and a turtle. Participants again were instructed to respond as quickly as possible while also maintaining response accuracy. Specific instructions were, "Look! You see a [target 1] and a [target 2]. They will appear on the center of screen, sometimes a [target 1], sometimes a [target 2]. You will push *this* key as soon as possible [pointing to left "Shift" key] only when [target 1] appears. You will have to push *this* key as soon as possible [pointing to right "Shift" key] only when [target 2] appears. If you make a mistake, the computer will make a noise. Push the keys as quickly as possible, but try to make as few mistakes as you can." In the two-choice reversal condition, the target stimulus–response relations were reversed so that participants now needed to press [key 1] to [target 2] and vice versa. For the four-choice condition, comparable instructions that included the four stimuli and responses were used. Following administration of five practice trials (two-choice) to acclimate participants to the choice RT paradigm, participants completed 20 experimental trials for each condition (two-choice, two-choice reversal, and four-choice). The stimulus pictures were randomized within each condition, and condition type was presented blocked, with a fixed order across participants (two-choice, two-choice reversal, and then four-choice).

Results

Design

The mean and standard deviation in RT for each individual participant was calculated for each condition and task. Practice trials were excluded from the calculations, as were RTs from trials in which participants pressed the wrong key. In Table 1 are the means and standard deviations of the percentages correct by task condition type. Response accuracy for all four age groups on the seven task condition types was quite high. Each response with a response latency exceeding the mean by more than 2 standard deviations (for each participant and each task separately) was excluded from the RT analyses (fewer than 2% of all trials) because the participant was considered off-task for that trial. Table 1 shows the means and standard deviations for RT latency in different task conditions. Because RT data were positively skewed, as is typical, statistical tests were conducted on RT data after log10 transformation.

Table 1. Group performance on the six RT tasks for the four age groups

RT task	4-year-olds		5-year-olds		6-year-olds		Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Accuracy (%)								
ODR	97.0	3.9	95.8	4.9	94.5	4.8	97.0	4.6
CDR	95.3	6.5	98.1	3.4	97.1	3.6	98.4	2.6
SDR	93.1	7.5	96.0	4.2	97.6	3.5	98.0	4.1
CR2	95.6	6.1	96.0	5.7	96.6	4.1	96.1	4.0
CRR	89.6	9.0	92.2	7.7	92.9	6.4	97.1	4.3
CR4	88.0	13.3	92.9	11.9	95.8	5.7	95.0	8.0
Reaction time (ms)								
SR	740	162	580	144	467	85	270	31
ODR	979	181	804	173	665	104	374	42
CDR	1112	287	900	163	758	111	409	48
SDR	1790	581	1198	254	949	139	449	51
CR2	1145	185	947	160	816	92	469	56
CRR	1472	300	1161	245	1022	173	503	66
CR4	2485	783	1652	437	1346	319	704	132

ODR, object discrimination; CDR, color discrimination; SDR, spatial discrimination; CR2, two-choice; CRR, two-choice reversal; CR4, four-choice; SR, simple reaction.

Multilevel modeling with PROC MIXED in SAS software was used to address the study hypotheses, with the log transformed RT latency as the dependent variable, with age and sex as between-participants factors and the various task condition manipulations as levels of repeated within-participant factors. To examine possible effects of a confounding of sex with age, models including the Age Group × Sex interaction and the main effect of sex were run for each task condition type. None of these effects was significant for any task condition type (all *p*s > .05); therefore, the influence of sex was not considered further.

The mixed-factorial, multilevel modeling analyses were performed twice: one set focusing on the RT differences between children and adults, where age group was treated as a two-level between-participants factor, and another set focusing on the age-related differences among the very young children, where age was treated as continuous. To examine task condition effects, four planned comparisons using the within-participant factors were conducted. The first comparison examined the impact of suppressing a response in light of a discriminative stimulus by comparing RT in the simple RT task with RTs across the conditions of the discrimination RT task. The second comparison addressed the impact of discriminative stimulus type, while holding response constant, by comparing RT latency in the object identity, color, and spatial orientation conditions. The third comparison examined the effect of response reversal by contrasting RTs from the two-choice and two-choice reversal conditions of the choice RT task. Finally, the last contrast examined the impact of complexity by comparing RTs from the two-choice and four-choice conditions in the choice RT task. To maintain family-wise error rates in these planned comparisons, the Bonferroni correction was applied, dividing alpha critical by the number of comparisons (.05/4 = .0125). Unless otherwise noted, all significant effects are reported as $p < .0125$.

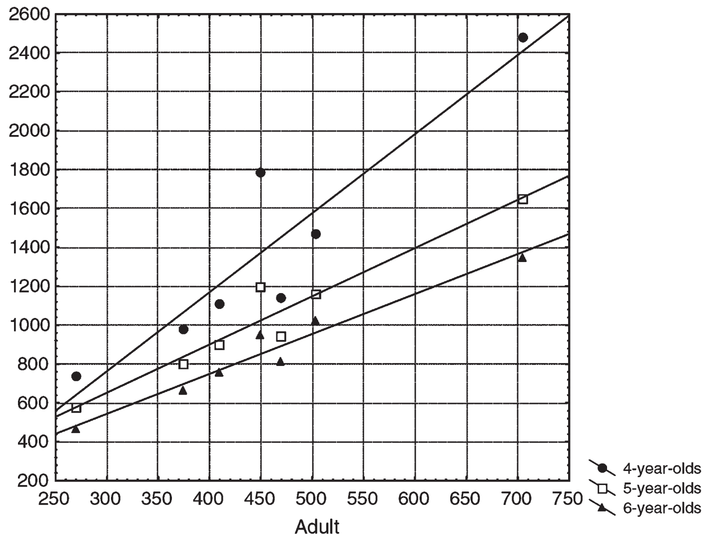


Figure 1. Linear relation between RT and task type in children and adults for each child group. Each slope is fitted to seven data points representing the seven RT tasks.

If Age × Task Condition interactions were significant, then multilevel models were performed twice: without transformation and with transformation using the approach described by Madden et al. (1992) and Ridderinkhof and van der Molen (1997). The transformation was accomplished by dividing a participant's RT by the parameters of the best-fitting regression function (the slowing coefficients of each of the child groups). The slowing coefficients (m_{age}) were calculated for each of the three child groups by regressing the mean RTs of the seven tasks for each child group on adult RTs (e.g., the mean RT of 4-year-olds on each of the seven tasks was regressed on the mean RT of adults on each of the seven tasks). Adult RTs accounted for 85, 93, and 96% of the variability of RTs of the 4-, 5-, and 6-year-old groups, respectively. In addition, the m_{age} values decreased with advancing age group, with the coefficient being 4.07 for 4-year-olds, 2.48 for 5-year-olds, and 2.06 for 6-year-olds. The relation of adult RT to that of each of the three child groups is illustrated in Figure 1, where the mean RT for each of the child groups on each task is plotted against that of adults on the corresponding task. The transformed RTs were then used in the multilevel models to examine whether significant age by task condition differences in RT remained after accounting for the effect of generalized developmental slowing represented in the Brinley function.

Age group-related differences between children and adults

Mean accuracy and RT for each of the RT tasks and conditions are shown in Table 1. Note that, not surprisingly, variability in RT was higher in the young children; therefore, the Sattherwaite option was used in the multilevel models to adjust for the unequal variances across groups. A summary of the planned contrast results is provided in Table 2. In the planned comparison addressing the influence of suppressing a response to a discriminative stimulus, the main effect of age group was significant, $F(1, 177) = 356.18$, $\eta_p^2 = .67$, indicating that there are age group-related differences in RT between children and adults.

Table 2. Summary of mixed-factorial effects

	Main effect of age group	Main effect of task	Age Group × Task Condition interaction	Brinley transformed: Age Group × Task Condition interaction
Age Group (children vs. adults) × Task Condition				
Suppression: SRT vs. DRT (ODR, CDR, SDR)	**356.18**	**1981.18**	**20.87**	1.57
Discriminative stimulus type: ODR vs. CDR vs. SDR	**429.13**	**399.75**	**76.91**	**59.06**
Response reversal: CR2 vs. CRR	**483.14**	**219.92**	**58.05**	**34.26**
Complexity: CR2 vs. CR4	**359.19**	**1155.94**	**42.10**	**6.64**
Age Group (young children only) × Task Condition				
Suppression: SRT vs. DRT (ODR, CDR, SDR)	**249.73**	**1592.10**	0.38	N/A
Discriminative stimulus type: ODR vs. CDR vs. SDR	**244.36**	**304.51**	**26.97**	**17.45**
Response reversal: CR2 vs. CRR	**172.38**	**322.91**	1.08	N/A
Complexity: CR2 vs. CR4	**259.06**	**888.75**	**61.84**	**16.61**

Significant *F* values are in bold type.

RT did vary significantly by task type, $F(1, 74.7) = 1981.18$, $\eta_p^2 = .96$, and the task type effect differed significantly in children and adults, $F(1, 74.7) = 20.87$, $\eta_p^2 = .22$. As expected, children required greater latency to respond than did adults. RTs were faster on the simple RT task where participants responded to all stimuli than when participants were required to suppress responding to a discriminative stimulus, to differing degrees in young children and adults. Children's RT then was transformed using the Brinley function to obtain slowing coefficients. After the transformation, the age group by condition type interaction no longer was significant, $F(1, 72.4) = 1.57$, $\eta_p^2 = .02$, suggesting that the observed slowing effect for suppressing a response to a discriminative stimulus can be accounted for by the global difference in processing speed.

In the contrast addressing the impact of stimulus type, there were significant main effects of age group, $F(1, 165) = 429.13$, $\eta_p^2 = .72$, and stimulus type, $F(2, 230) = 399.75$, $\eta_p^2 = .78$. Again, RT latencies were longer in children than in adults, and RTs were longest in the spatial orientation condition. Furthermore, participants took more time to press the key in response to color than to object identity. Most important, the interaction of stimulus type and age group was significant, $F(2, 230) = 76.91$, $\eta_p^2 = .40$. After the children's RT data were transformed further using the Brinley function to obtain the slowing coefficients, the original interaction involving age group by condition type remained significant, $F(2, 229) = 59.06$, $\eta_p^2 = .34$, suggesting a process-specific slowing effect in young children relative to adults.

Contrasts were conducted to further delineate the nature of this age group by task condition interaction; that is, direct (within-participant) contrasts between object discrimination and color discrimination conditions and between object discrimination and spatial orientation discrimination conditions were run. Because all three conditions require object recognition and discrimination, the color discrimination and spatial orientation discrimination conditions require additional cognitive resources relative to the object discrimination condition due to the added color or spatial processing demands. Therefore, the follow-up condition contrasts were conducted relative to the object discrimination condition, where the comparisons were selected to represent the "cost" of color or spatial orientation discrimination processing beyond the processing required for object discrimination.

In color discrimination follow-up contrasts, task type was significant for children, $F(1, 322) = 58.83$, $\eta_p^2 = .15$, and for adults, $F(1, 69.7) = 32.94$, $\eta_p^2 = .32$. The color discrimination contrast remained significant after the transformation using the Brinley function for children, $F(1, 318) = 35.47$, $\eta_p^2 = .10$, and for adults, $F(1, 70.6) = 29.12$, $\eta_p^2 = .29$. In the spatial orientation discrimination follow-up contrast, task type was significant for both children and adults, $F(1, 322) = 765.28$, $\eta_p^2 = .70$, and $F(1, 69.7) = 135.62$, $\eta_p^2 = .66$, respectively. When the children's RT data were transformed further using the Brinley function to obtain the slowing coefficient, this contrast remained significant in both children and adults, $F(1, 318) = 629.57$, $\eta_p^2 = .66$, and $F(1, 70.6) = 130.45$, $\eta_p^2 = .65$, respectively.

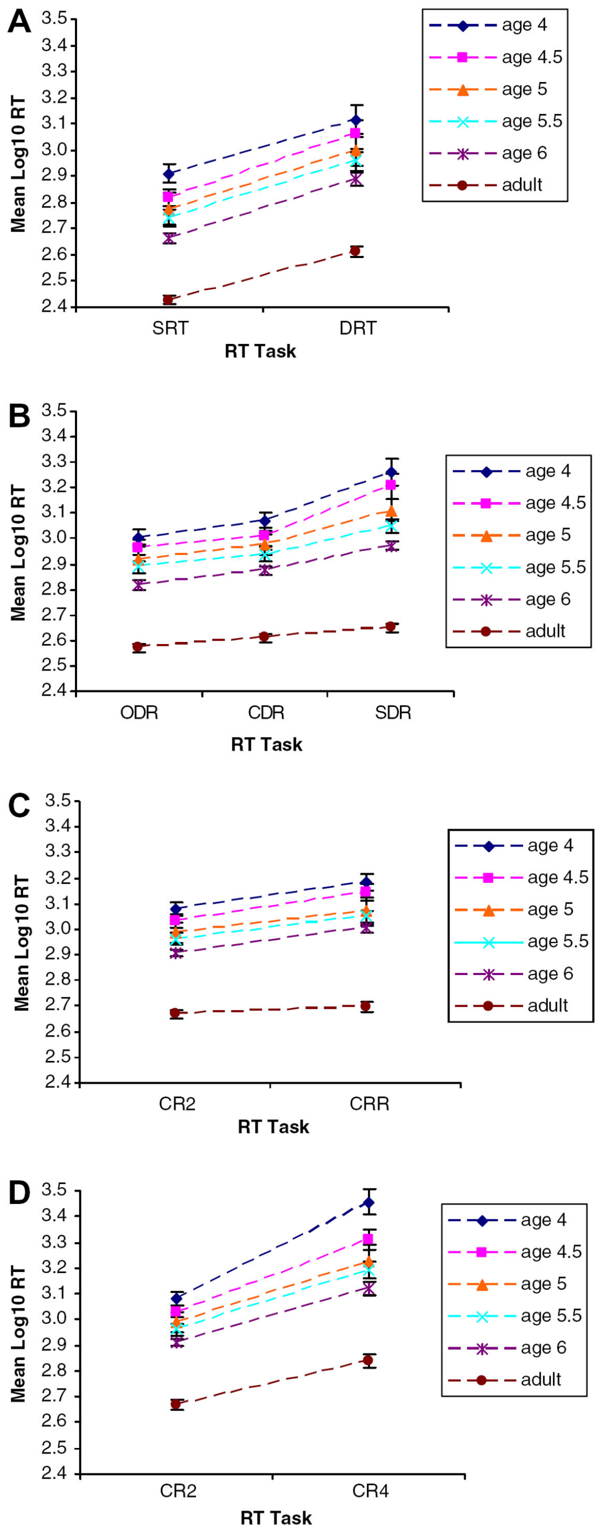
In the models addressing response reversal, the main effects of both age group, $F(1, 175) = 483.14$, $\eta_p^2 = .73$, and condition type, $F\ (1, 72.8) = 219.92$, $\eta_p^2 = .75$, were significant. As expected, RTs were slower in children than in adults and were slower in the condition where the stimulus–response association was reversed relative to the two-choice condition. The age group by condition type interaction also was significant, $F(1, 72.8) = 58.05$, $\eta_p^2 = .44$, indicating that the difference in RTs in the response reversal condition was larger (RTs were more greatly slowed) in children than in adults. After the children's RT data were transformed further using the Brinley function to obtain the slowing coefficient, the Age Group × Condition Type interaction remained significant, $F(1, 66.3) = 34.26$, $\eta_p^2 = .34$, consistent with a process-specific slowing effect for response reversal in children relative to adults.

Finally, in the complexity contrast, main effects of age group, $F(1, 138) = 359.19$, $\eta_p^2 = .72$, and of complexity, $F(1, 100) = 1155.94$, $\eta_p^2 = .92$, were significant. As expected, RTs were slower in children than in adults and were slower in the four-choice condition than in the two-choice condition. The interaction between age group and task condition was significant, $F(1, 100) = 42.10$, $\eta_p^2 = .30$, indicating that the difference in RT related to complexity was larger in children than in adults. This interaction effect was robust after the children's RT data were transformed further using the Brinley function to obtain the slowing coefficient, $F(1, 77.3) = 6.64$, $\eta_p^2 = .08$, again suggesting a process-specific slowing effect of complexity in young children compared to adults.

Age-related differences among young children

Mean RTs (after log10 transformation) by age and condition, grouped by planned contrast, are shown in Figure 2. In the planned contrast addressing the influence of suppress-

Figure 2. (Page 160) Relation between RT and task type for each of the comparisons in adults and five child age groups (4-, 4.5-, 5-, 5.5-, and 6-year-olds). (A) Mean performance on the simple RT task (SRT) and the discrimination RT task (DRT). (B) Mean performance on the RT tasks requiring discrimination of color (CDR), object identity (ODR), and spatial orientation (SDR). (C) Mean performance on the simple two-choice stimulus–response condition (CR2) and its reversal (CRR). (D) Mean performance on the two-choice and four-choice conditions (CR2 and CR4). Vertical bars denote .95 confidence intervals.


A
B
C
D
Mean Log10 RT
RT Task
SRT
DRT
ODR
CDR
SDR
CR2
CRR
CR4
age 4
age 4.5
age 5
age 5.5
age 6
adult
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4

ing a response to a discriminative stimulus, the main effect of age was significant, $F(1, 164) = 249.73$, $\eta_p^2 = .60$, indicating that there are age-related differences in RTs among children. RTs also varied significantly by task type, $F(1, 164) = 1592.1$, $\eta_p^2 = .91$, although the interaction between age and task type was not significant, $F(1, 164) = 0.38$, $p = .54$. RTs decreased as age increased, and RTs were faster when participants needed to respond to all stimuli than when they needed to suppress responding to a discriminative stimulus.

In the planned comparison addressing the impact of stimulus type, there were significant main effects of age, $F(1, 328) = 244.36$, $\eta_p^2 = .43$, and of stimulus type, $F(2, 328) = 304.51$, $\eta_p^2 = .65$, on RT. Again, RT latencies decreased as age increased, and RTs were longest in the spatial orientation condition. Furthermore, participants took more time to press the key in response to colored objects than in response to those differing only in identity. Critically, the interaction of stimulus type and age was significant, $F(2, 328) = 26.97$, $\eta_p^2 = .14$. This interaction remained significant after the children's RT data were transformed further using the Brinley function to obtain the slowing coefficients, $F(2, 328) = 17.45$, $\eta_p^2 = .10$, suggesting a process-specific slowing effect of stimulus type in young children.

The same follow-up contrasts to further delineate the nature of the age by task condition interactions were conducted as for children versus adults to investigate the cost of color discrimination and spatial orientation processing in 4-, 5-, and 6-year-olds. In the color discrimination follow-up contrast, the interaction of age and stimulus type was significant for all three age groups, $F(1, 328) = 15.24$, $\eta_p^2 = .04$, $F(1, 328) = 47.49$, $\eta_p^2 = .13$, and $F(1, 328) = 57.08$, $\eta_p^2 = .15$, respectively. The age by stimulus type interactions was marginally significant for 4-year-olds, $F(1, 328) = 6.25$, $p = .04$, $\eta_p^2 = .02$, after the children's RT data were transformed using the Brinley function, and they were significant at the stated level for 5-year-olds, $F(1, 328) = 24.47$, $\eta_p^2 = .07$, and 6-year-olds, $F(1, 328) = 35.65$, $\eta_p^2 = .10$. The same pattern was observed for the spatial orientation discrimination follow-up contrast, where the Age × Stimulus Type interaction again was significant for 4-, 5-, and 6-year-olds, $F(1, 328) = 409.72$, $\eta_p^2 = .56$, $F(1, 328) = 820.43$, $\eta_p^2 = .71$, and $F(1, 328) = 581.95$, $\eta_p^2 = .64$, respectively. When the children's RT data were transformed further using the Brinley function to obtain the slowing coefficient, the age by condition interaction was robust for 4-, 5-, and 6-year-olds, $F(1, 328) = 297.41$, $\eta_p^2 = .48$, $F(1, 328) = 623.37$, $\eta_p^2 = .66$, and $F(1, 328) = 473.08$, $\eta_p^2 = .59$. Taken together, these results suggest a process-specific slowing effect for color and spatial orientation information within the very young age group.

In the response reversal comparison, the main effects of age, $F(1, 164) = 172.38$, $\eta_p^2 = .51$, and condition type, $F(1, 164) = 322.91$, $\eta_p^2 = 0.66$, were significant. RTs decreased as age increased and were slowest in the condition where the stimulus response association was reversed. In contrast to the adult versus child group comparison, the age by condition type interaction was not significant among young children, $F(1, 164) = 1.08$, $p = .30$. Finally, in the complexity contrast, main effects of age, $F(1, 164) = 259.06$, $\eta_p^2 = 0.61$, and of complexity, $F(1, 164) = 888.75$, $\eta_p^2 = .84$, were significant. As expected, RTs decreased as age increased and were slower in the four-choice condition than in the two-choice condition. As in the child–adult contrast, the interaction between age and task condition was significant, $F(1, 164) = 61.84$, $\eta_p^2 = .27$, indicating that the difference in RT related to complexity was larger in younger children. This interaction effect was robust after the children's RT data were transformed further using the Brinley function to obtain the slowing coefficient, $F(1, 164) = 16.61$, $\eta_p^2 = .09$, consistent with a process-specific slowing effect of complexity in young children.

Discussion

Not surprisingly, there were clear age-related differences in processing speed not only between young children and adults but also among the very young children. These age-related differences were observed robustly across tasks and conditions. Results from use of the regression method further support the hypothesis that there are global, age-related differences in processing speed where, similar to Kail and others (Kail, 1991; Kail and Park, 1992; Miller and Vernon, 1997), the magnitude of the slowing coefficient decreased with increasing age. However, using the transformation method of Madden et al. (1992) and Ridderinkhof and van der Molen (1997) with the Brinley function, not only were global age-related differences evident, but also task-specific, age-related differences in processing speed were revealed. In particular, in comparing children and adults, the age-related differences in RT when the Brinley method was applied were apparent under four conditions: when stimuli differed in color orientation, when stimuli differed in spatial orientation, when a previously learned stimulus–response rule was reversed, and when the stimulus–response rule was more complex. Among the young children, process-specific, age-related differences were evident when the stimuli differed in color or spatial orientation and when the stimulus–response array was more complex. The obtained pattern of results suggests that there are different sources of slowing of processing speed, some of which are global and due to age generally and some of which are related to task-specific demands that elicit differential cognitive processing somewhat differentially across developmental periods.

On the one hand, there is substantial evidence that a global developmental mechanism influences the reduction in RT observed across child development and the transition to adult maturity. Often this mechanism is called a "general speed factor" that usually is extracted from a data covariance matrix using factor-analytic techniques in individual difference research. This finding is in keeping with Jensen (1988), who stated that "in several multivariate studies [of response latency] … that I have seen, however, one feature is quite clear: there is always a large General Speed factor along with other relatively smaller factors associated with particular processes" (p. 120). Results from regression techniques in developmental research where clear age-related differences in general processing speed factor are observed (Cerella and Hale, 1994; Kail and Salthouse, 1994) provide solid evidence for this view, as do findings from meta-analytical studies that collapse across samples, ages, and methods (Hale, 1990; Kail, 1991; Kail and Salthouse, 1994). This general speed factor was evident across task types and was the only contributor to performance on RT task conditions that required discrimination and response to relevant stimuli and required response suppression to irrelevant stimuli, perhaps the most widely studied RT experimental manipulation.

However, a mechanism of general slowing with advancing age does not appear to be sufficient to explain the full range of age-related differences in processing speed reported in the literature (Cowan et al., 1998; for detailed discussion of this issue, see also Fisk & Fisher, 1994). Many investigators have proposed that some component cognitive processes are affected more by age than are others (e.g., Fisk et al., 1992; Madden et al., 1993). In other words, task-specific differences that presumably reflect the latent cognitive processing demands and concomitant brain activation patterns also influence the observed reduction in RTs across child development.

This finding is consistent with recent conceptions of neural development across childhood termed *heterochronicity* (Casey et al., 2005; Farber, 1993; Gogtay et al., 2004). Heterochronicity means that different brain structures and areas follow temporally distinct maturational trajectories that should be manifest on tasks that demand the concomitant distinct cognitive processes subserved by these brain structures. For example, higher order association areas, such as the prefrontal and lateral temporal cortices, mature after the lower order somatosensory and visual cortices mature (e.g., Casey et al., 2005; Gogtay et al., 2004). Brain regions that support more primary functions, such as motor and sensory systems, reach maturation earlier than do regions that subserve more complex and integrative functions such as spatial orientation and executive control (Casey et al., 2005). Correspondingly, these developmental differences in brain maturation can be observed most readily by contrasting task performance that differentially requires discrete cognitive processes such as RT tasks where the stimulus–response rules can be manipulated systematically.

According to the heterochronicity view, age-related differences in RT tasks that differentially demand processing by less developed brain areas in children should be more pronounced than those age-related differences in RT tasks that demand processing by mature brain areas. If RT tasks demand processing by brain areas that mature rapidly between the intervals of the ages studied, then more pronounced age-related differences in these RT task conditions should be observed between these age groups that flank the developmental period. Here not only does a general speed factor contribute to the observed age-related differences in RT, but also there is further contribution of task type, a proxy for the specific cognitive processing demands and underlying neural activation patterns.

In this study, the RT task demands were varied systematically in the demands on perceptual, visuospatial, and executive control. In particular, age-related differences in RT task performance between children and adults and among young preschool children were evident where the processing of color or spatial orientation was required relative to conditions that differed in discrimination of object identity alone. The processing of color is linked closely to the occipital secondary sensory association cortex, whereas the processing of spatial orientation information is related to the lateral parietal–temporal–occipital cortex, a tertiary association area. In support of the heterochronicity framework, the occipital secondary sensory cortex has been demonstrated to mature earlier than the tertiary lateral parietal–temporal–occipital cortex (Casey et al., 2005; Farber, 1993), although both are mature well before 4 years of age. Furthermore, efficiency of color processing reaches mature levels of performance (Brown, 1990) before visual spatial skills (Casey et al., 2005; Farber, 1993; Stiles et al., 2002), again before 4 years of age. The graded difference in mean RTs within this age group reflect these age-related differences in the component cognitive processing demands. A similar argument is substantiated for the comparable pattern of observed task-specific, age-related differences in the processing stimulus–response information that varies in response complexity (Halford et al., 1998).

The discrepancy comes in considering the pattern of results for the reversal of stimulus–response contingencies, often considered a component process of executive control. Pronounced age-related differences were noted between children and adults on the RT tasks that differed in the demand to reverse responding to the previously discriminative stimulus. However, no age-related, task-specific differences in RT performance were noted among preschool children who differed in age. Here the maturation between children and adults in the brain systems that subserve executive control is also substantially more protracted than are either secondary somatosensory areas or the lateral parietal temporal junction (e.g., Casey et al., 2005), as is the age at which mature performance often is observed (Espy et al., 2001; Welsh et al., 1991).

Many young children show rudimentary abilities to reverse responses to a newly relevant stimulus–response contingency that depends on task type (e.g., Espy and Cwik, 2004; Espy et al., 1999; Zelazo and Mueller, 2002). Certainly, even among those who demonstrate proficiency, there is highly variable efficiency among individual children (Espy et al., 2006). Relatedly, there are large individual differences in the development of coherence in brain electrical signals that are generated during executive task performance during the preschool period (Wolfe & Bell, 2003). These reversal skills and concomitant prefrontal brain areas that subserve these abilities are under active development during the young ages assessed here. The observed pattern of findings suggests that the process-specific, heterochronic aspect of RT, at least within the age group, is obscured until proficiency is stable. That is, the exceedingly protracted prefrontal system development across this very young developmental period manifests in response reversal processes that are not sufficiently synchronized within this age period to reveal task-specific, age-related differences among 4-, 5-, and 6-year-olds.

There are several study limitations that merit consideration. First, the order of stimulus presentation was not randomized or counterbalanced because fixed order designs are preferred with studies of individual differences in very young children (Carlson & Moses, 2001). Practice effects and order of task/condition presentation effects might have influenced the obtained pattern of results. Given this individual difference design, however, even if order effects are present, they are expected to be distributed equivalently across groups and individuals. Furthermore, only limited demographic information was collected in this study, and this does not preclude systematic differences in social background variables among age groups that might have influenced the obtained pattern of results. However, given the mixed adult and very young child sample, the role of the social environment in performance is not straightforward to evaluate or statistically control. These limitations notwithstanding, these findings suggest that a global developmental mechanism, although an important contributor to RT task performance, does not account fully for the full range of task-specific, age-related differences in the processing speed that were observed in adults and young children. The observed process-specific, age-related differences in processing speed generally are consistent with the principle of heterochronicity of human brain development (Casey et al., 2005).

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