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The Development of Selective Inhibitory Control Across the Life Span

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A modification of the stop-signal task was used to investigate the development of selective inhibitory control. A group of 317 participants, age 6 to 82 years, performed a visual choice reaction time (go) task and attempted to selectively inhibit their response to the go task when hearing one of two randomly presented tones (1000 Hz, 250 Hz), each presented on 20% of trials. Measures of response execution and inhibi-

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tion were assessed by using reaction times to the go signal (GoRT) and stop signal (SSRT), respectively. Results indicated that SSRT gets faster with increasing age throughout childhood, with pronounced slowing in older adulthood. In addition, strong evidence was obtained for age-related speeding in GoRT throughout childhood, with marked slowing throughout adulthood. Subsequent hierarchical regression analyses illustrated that the age-related changes in selective inhibitory control could not be explained simply by overall slowing or speeding of responses. Findings are discussed in regard to the decay and maturation of selective inhibitory control across the life span.

Inhibition is a central concept to theories of development and aging that interpret cognitive difficulties of young children and the elderly as deficits in inhibitory processing (e.g., Bjorklund & Harnishfeger, 1990; Hasher & Zacks, 1988; Kramer, Humphrey, Larish, & Logan, 1994). Moreover, deficient inhibition is central to current theories of psychopathology and impulsivity (e.g., Barkley, 1997; Gray, 1987; Patterson & Newman, 1993; Quay, 1997). The concept of inhibition is discussed in many different forms and is measured in a variety of ways (e.g., Dagenbach & Carr, 1994; Kramer et al., 1994). In this study we focused on the type of inhibition that is manifest in the stop-signal task (Lappin & Eriksen, 1996; Logan & Cowan, 1984; Logan Cowan, & Davis, 1984; Ollman, 1973; Osman, Kornblum, & Meyer, 1990; Vince, 1948). This type of inhibition is conceptualized as one of several internally generated acts of control in the repertoire of a higher order executive system that regulates the operations of the human information processing system and permits self-regulation (e.g., Goldman-Rakic, 1987; Logan, 1985; Shallice, 1982). It is defined as the ability to stop (suddenly and completely) a planned or ongoing thought and action (Logan, 1994). This central act of control is required in many real-life situations in which an individual's planned or ongoing actions are suddenly rendered inappropriate by unanticipated events or changes in the immediate environment (e.g., a batter in a baseball game must halt his or her swing to adjust to a pitch that has just broken out of the strike zone).

One clear advantage of using the stop-signal task over other neuropsychological measures of inhibition (e.g., Matching Familiar Figures Test, Go–No Go Task, Conners' Continuous Performance Test) is that the underlying model provides a way of measuring the latency of the internally generated act of control (stop-signal reaction time, or SSRT) even though successful inhibition produces no overt behavior. In the stop-signal task, SSRT is the primary performance variable and indicates the speed of the inhibition process. SSRT does not provide all the information yielded by the stop-signal task but is highly informative because changes in SSRT characterize important differences between groups of individuals (e.g., impulsive adults have longer SSRTs than nonimpulsive adults; Logan, Schachar, & Tannock, 1997) and between individuals tested under different conditions (e.g., stimulant medication improves SSRT compared with placebo in children with attention deficit hyperactivity disorder; Tannock, Schachar, Carr, Chajczyk, & Logan, 1989; Tannock, Schachar, & Logan, 1995).

Research using the stop-signal paradigm to date has focused primarily on nonselective or basic inhibitory control, which involves the inhibition of all responses whenever a stop signal occurs (e.g., May & Hasher, 1998, Ridderinkof, Band, & Logan, 1999; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). In comparison, selective inhibitory control is a more cognitively demanding process requiring the inhibition of some responses without the inhibition of others (De Jong, Coles, & Logan, 1995; Logan, Kantowitz, & Riegler, 1986). For example, participants engaged in a choice reaction time task could be presented with a stop signal that requires the inhibition of responses to one stimulus but not to the other. In everyday life, selective inhibitory control often is required when driving. For instance, unexpected road conditions (e.g., a patch of ice vs. a physical obstruction) require the driver to quickly decide whether it is better to keep driving or to halt. Such adaptive acts of control depend on an intricate interplay between activation and inhibitory control, affording a much more flexible inhibition process than nonselective, stop-all inhibition. In this study we investigated selective inhibitory control.

Developmental change in the speed of responding is well documented with a wide variety of reaction time tasks (e.g., Cerella & Hale, 1994; Hale, 1990; Kail, 1993). Generally, response speed increases throughout childhood, reaching a peak in early adulthood, and then decreases gradually throughout adulthood (Hale, 1990; Williams et al., 1999). Until recently, developmental change in inhibitory control was unclear. The relatively few studies available yield only limited evidence of age-related speeding of response inhibition processes throughout childhood (Band, 1996; Band & van der Molen, 2000; Jennings, van der Molen, Pelham, Debski, & Hoza, 1997; Oosterlaan & Sergeant, 1997; Schachar & Logan, 1990) and of age-related slowing across adulthood (Kramer et al., 1994; May & Hasher, 1998). By contrast, a recent study of life-span changes in nonselective inhibitory control revealed marked speeding of inhibitory control processes across childhood through adolescence with only limited evidence of slowing in older adults (Williams et al., 1999). Consistent with previous research, clear evidence of age-related speeding of response execution throughout childhood and adolescence and marked slowing throughout adulthood was found (Williams et al., 1999). Previous studies with the stop-signal task provide a possible explanation for this unexpected limited evidence of slower go-task responding in older adults. Kramer et al. (1994) and May and Hasher (1998) used more complex response execution (go) tasks and observed a more marked slowing of SSRT throughout adulthood compared with the study conducted by Williams and colleagues (1999; by an average of 90 msec vs. 20 msec). They suggested that an overall increase in cognitive demands could have resulted in greater difficulty controlling the stopping process, particularly in the elderly.

In this study we investigated the impact of increased task complexity on developmental changes in inhibitory control by using a variant of the stop-signal task to measure selective inhibitory control. The response inhibition (stop) task can be made more complex, much like response execution (go) tasks can be made more complex. The response inhibition task can be made more complex at the perceptual end by requiring discrimination between more than one presented stop signal, and it can be made more complex at the motor end by requiring discrimination among responses (some of which should be inhibited and others of which should not be inhibited; De Jong et al., 1995). In this study we examined the perceptual aspect of selective inhibitory control by adding a second tone to the basic stop-signal task and instructing participants to inhibit response execution whenever presented with the designated or selected stop-signal tone and to continue to respond to trials during which the nonselected stop-signal tone is presented. When we used this procedure, the response inhibition task became a choice reaction time task, similar to the response execution (go) task, which required the discrimination between the letters *X* and *O*. Studies to date on selective inhibitory control are limited and have been restricted to adult participants (De Jong et al., 1995; De Jong, Coles, Logan, & Gratton, 1990; Logan et al., 1986; van der Veen, van der Molen, & Jennings, 2000). No study to date has examined this construct in children or across the entire life span.

This study was designed to investigate selective inhibitory control in a community sample comparable to that used in a previous developmental study of nonselective inhibitory control in terms of age (6- to 82-year-olds), demographics, and recruitment source (Ontario Science Centre; Williams et al., 1999). Our goal was to ensure adequate statistical power to investigate age-related changes in selective inhibitory control. We predicted that the observed latencies of response execution in the selective stop-signal task and the developmental changes in their latency would be comparable to those observed in other developmental studies that used a similar forced-choice reaction time response execution task (e.g., Band & van der Molen, 2000; Ridderinkof et al., 1999; Williams et al., 1999). By contrast, we predicted a more marked slowing of SSRT, or response inhibitory control across adulthood, by using the selective stop-signal task due to the increased cognitive demands at hand before a response is inhibited (i.e., requiring participants to discriminate between stop signals and attempting to inhibit to one signal and continue responding to the other).

METHOD

Participants

Throughout a 2-week testing period in July 1998, 328 visitors to the Ontario Science Centre (Toronto, Canada) were recruited for participation. Of these individuals, 11 (3%) were excluded from analyses because of extreme scores (three or more standard deviations from the mean) on the two primary outcome variables (6 for go-signal reaction time [GoRT] and 5 for SSRT), leaving data collected from the remaining 317 participants for analysis. Volunteers with hearing, vision, or motor function impairments and those who did not speak at least some English or French could not participate because the study design was not adapted for such special needs. In addition, individuals who were on medication or who had a self-disclosed psychiatric illness were also excluded.

The participants ranged in age from 6 to 82 years. There were 157 males and 160 female participants. As shown in Table 1, the gender distribution across the seven age groups was fairly uniform. As might be expected of visitors to a science center, the majority of participants had a reasonably strong educational background: Virtually all of the participants under 17 years of age were currently attending school; 23% of the young adults had completed secondary school and 65% had completed some form of postsecondary education; and most of the adults had completed some postsecondary education (80% of the middle adult group, 90% of the older adult group, and 47% of the seniors group). English was the most common language used by participants, with 83% of participants citing it as their primary language spoken at home. Other languages used as the main form of communication at home included French (4%), Chinese (3%), Spanish (2%), Italian (1%), and German (1%). Accordingly, a wide range of ethnic groups were represented in the sample.

Apparatus and Stimuli

Five stand-alone, IBM-compatible, desktop computers were used to present the stimuli. Each of these five testing units was provided with adjustable padded headphones through which two distinct auditory signals could be presented without hindrance from potential background noise. In addition, each computer was connected to a hand-held response box (14 cm × 8.5 cm × 3.5 cm) that contained three single-pole double-throw buttons. These buttons were arranged on the top of the box in a linear formation with the two outermost buttons individually labeled with the visual stimuli for the go task.

The visual stimuli for the go task were the uppercase letters *X* and *O*, presented in the center of the screen for 1000 msec. Each go-task stimulus was preceded by a 500-msec fixation point, also presented in the center of the screen. Two 500-msec auditory tones (1000 Hz, 250 Hz) were generated by the computer, each presented on approximately 20% of trials and delivered through headphones at a comfortable volume for listening. One of these two tones was designated as the selected stop-signal tone; the nonselected stop-signal tone was to be ignored. The stop-signal delay (i.e., the interval between the presentation of the go signal and the selected stop signal) was changed dynamically after each designated stop-signal trial based on the performance of the participant (Logan et al., 1997). Stop-signal delay was initially set at 250 msec and was adjusted in 50-msec steps in the following manner: The delay increased by 50 msec if the participant inhibited successfully to the selected stop signal (making it harder to inhibit on the next stop-signal trial) and decreased by 50 msec if the participant failed to inhibit (making it easier to inhibit on the next selected stop-signal trial). This online tracking system of success in selective inhibitory control was designed to force a "tie" finish between response execution and response inhibitory control. Thus, the goal of the tracking algorithm was to allow participants to successfully inhibit responding to the response execution task on approximately 50% of the selected stop-signal trials. This was necessary for the estimation of SSRT, which is calculated from the mean stop-signal delay subtracted from the mean GoRT (see appendix of Williams et al., 1999). Mean response execution speed (i.e., GoRT) was calculated based on the response speeds during those trials in which an auditory tone (both selected and nonselected) was absent, which followed standard practice (e.g., Logan & Burkell, 1986; Logan & Cowan, 1984; Logan et al., 1997; Osman et al., 1990; Schachar, Mota, Logan, Tannock, & Klim, 2000; Williams et al., 1999).

The experimental task consisted of 192 trials divided into six 32-trial blocks. An equal number of *X*s and *O*s were presented in each block. The auditory tone stimuli (1000 Hz, 250 Hz tones) were presented on 12 (i.e., 38%) of the visual go-signal trials (distributed randomly in each block of 32 trials): 6 (19%) were 1000 Hz and 6 (19%) were 250 Hz tones. Each tone was presented half of the time with an *X* and half of the time with an *O*. The order in which the trials were presented was randomized separately for each participant. Once started, the program ran continuously, presenting one trial every 3.5 sec.

Two questionnaires were administered. One consisted of 14 demographic items including date of birth, gender, handedness, educational level, languages spoken at home, computer knowledge, health, accident history, learning difficulties, and prescribed medication. This questionnaire was used in a previous study on the development of nonselective inhibitory control (Williams et al., 1999). The second questionnaire consisted of age-appropriate versions of the Nowicki–Strickland Internal–External Locus of Control Inventory. This was used as a measure of generalized expectancies for internal versus external control of reinforcement among individuals. Data generated from these locus of control scales are not presented in this article, because there was no evidence of any relation between self-reported locus of control and any aspect of performance on the selective stop-signal task: Rather, those data will be the focus of a subsequent article.

Procedure

Located within the Laser Lab at the Ontario Science Centre, the testing area was secluded and divided into two separate areas: one for the completion of consent forms and questionnaires and the other for the completion of the selective stop-signal task. The initial portion of the experiment was done in the first area of the testing space and consisted of each participant reading and signing a consent form, as well as completing the demographic and personality questionnaires (approximately 10 min in length). An accompanying parent or guardian completed child questionnaires.

An experimenter accompanied each participant to the computer testing area to complete the selective stop-signal task. Participants were tested individually, and the experimenter read a uniform set of instructions, operated the computer, and monitored the participant's progress from start to completion of the computer task (approximately 20 min in length). Each participant completed one practice block before commencing six test blocks. Participants were told that they would see a fixation point followed by one of two letters (*X* or *O*) and that their task was to respond to the letter (by pressing the appropriate response button) as quickly as possible without making mistakes. Also, they were told that although they were to respond to the presented letters as quickly as possible, when the selected stop-signal tone was presented (either the higher sounding 1000 Hz or the lower sounding 250 Hz of the two auditory tones), they were to attempt to halt responding during that given trial. They were instructed not to wait for the auditory tones as they occurred randomly. Mean GoRT was displayed at the end of the practice block. The selection of the designated stop-signal tone was counterbalanced so that approximately an equal number of participants in each age group inhibited selectively to the high tone and to the low tone.

After completion of the practice block, the stop-signal delay was reset to 250 msec before the onset of the first test block. Mean GoRTs were displayed at the end of each test block to allow the participants to rest, as well as to enable the experimenter to monitor response execution task performance and restate instructions so that participants maintained relatively consistent GoRTs across the six experimental blocks.

Statistical Analysis

Due to the number of trials required by the tracking algorithm of the stop-signal task to adjust the stop-signal delay to the point where the participant is successfully inhibiting on 50% of stop trials, performance on the first block of the selective stop-signal task was excluded from analyses, leaving five test blocks for analysis. In addition, the total number of trials that contained an early anticipatory (invalid) response (i.e., a response within 200 msec of the onset of each response trial) was computed, and then these responses were excluded from further analyses. These anticipatory responses could occur on either response execution or response inhibitory control trials. We examined the stability of performance in SSRT and GoRT across the five experimental blocks as a reliability check of the data obtained by the selective stop-signal task. We then divided participants into seven different age groups based on their stage in the life cycle to allow for comparisons with data from previous studies (e.g., Kramer et al., 1994; Schachar & Logan, 1990; Williams et al., 1999). Response execution task accuracy was examined to check the validity of response execution performance, and accuracy of selective inhibitory control (assessed by the percentage inhibitory control given the nonselected stop-signal) was inspected across the different age groups by using an analysis of variance (ANOVA) approach. The effect of time on task performance was examined by comparing mean values of the outcome measures on the first two blocks of the task versus those of the last two blocks. ANOVAs were used to determine how age affected the execution and selective inhibition of prepotent responses (the dependent variables being GoRT and SSRT). We conducted subsequent trend analyses to investigate the hypothesis that SSRT and GoRT would have curvilinear (quadratic) relations with age. Planned comparisons of mean GoRTs and SSRTs for young adults (18–29 years) versus seniors (60–82 years) were performed to investigate whether the developmental trends in adulthood for selective inhibitory control would differ from those previously observed in nonselective inhibitory control (Williams et al., 1999). We used a hierarchical regression analysis to examine the curvilinear relations observed between age and the two criterion variables (SSRT and GoRT) and to compare developmental trends. Last, we used one-way ANOVAs to conduct secondary analyses on the effects of age on additional aspects of selective stop-signal task performance, including response variability, ability to inhibit, performance accuracy, and proportion of early (invalid) responses.

RESULTS

Reliability Check

Reliability coefficients were computed for the main dependent variables (SRRT and GoRT) across the five experimental blocks used in the analyses for both the entire data set and for each age group. Overall, $\alpha = 0.93$ for SSRT and $\alpha = 0.97$ for GoRT. The coefficients across all of the age groups were also consistently positive and high.

The data in Table 1 show that participants of all ages performed with proficiency in regard to correctly responding to the go signals (i.e., the letters *X* and *O*): The mean accuracy of responding was 96.2% (*SD* = 5%). In addition, the mean percentage inhibition given the selected stop-signal was 49.1% (*SD* = 6.6%), indicating that the tracking method was robust across the life span (i.e., inhibition on ~50% of selected stop-signal trials). The mean percentage inhibition given the nonselected stop signal was 4.1% (*SD* = 8.2%), indicating that participants were able to discriminate between the selected and nonselected stop signals.

TABLE 1
Description of Age Groups and Related Means and Standard Deviations for the Dependent Variables

				%EARLY		*SSRT*[a]		*GoRT*[a]		*SDGoRT*		*P(I/S)*		*P(I/N)*		*%CGR*	
Age	*Description*	*n*	*% Female*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
6–8	Early childhood	40	55	0.74	1.37	456	230	645	239	201	75	49.0	10.6	6.6	13.4	92.1	6.0
9–12	Middle childhood	62	40	0.68	1.50	336	159	462	122	125	42	48.0	6.4	3.0	5.4	93.8	6.2
13–17	Adolescence	54	65	0.37	1.23	261	111	390	91	100	34	48.4	4.2	2.2	4.2	95.9	4.8
18–29	Young adulthood	48	52	0.26	0.49	248	132	378	69	97	43	48.2	5.1	2.8	5.4	98.0	2.6
30–44	Middle adulthood	65	51	0.11	0.41	230	120	433	95	108	37	50.0	4.1	5.1	9.7	98.1	3.1
45–59	Older adulthood	23	39	0.75	2.29	232	122	494	146	128	38	47.8	9.7	6.2	8.2	98.1	4.2
60–82	Seniors	25	44	0.23	0.54	329	133	634	185	173	94	54.3	5.7	5.0	9.0	98.5	1.6
6–82	Total	317	50	0.42	1.20	295	164	470	163	127	61	49.1	6.6	4.1	8.2	96.2	5.0

Note. %EARLY = percentage of early (invalid) responses (calculated out of the total 192 trials); SSRT = stop-signal reaction time (milliseconds); GoRT = go-signal reaction time (milliseconds); SDGoRT = standard deviation of go-signal reaction time (milliseconds); P(I/S) = percentage of inhibitory control given the selected stop signal; P(I/N) = percentage of inhibitory control given the nonselected stop signal; %CGR = accuracy of go-task responding as percentage of correct go-signal responses.

[a] Mean stop-signal delay may be calculated from data presented; because SSRT = GoRT – Delay, it follows that Delay = GoRT – SSRT.

We conducted repeated measures ANOVAs comparing mean performance on the first (Blocks 2 and 3) and second (Blocks 5 and 6) halves of the experimental task across the seven age groups to examine the effects of time on task as well as potential time by age interactions. These analyses confirmed that time did not influence SSRT, $F(1) = .639$, $p = .43$; GoRT, $F(1) = 1.67$, $p = .20$; or inhibition to the nonselected stop signal, $F(1) = .001$, $p = .98$. Mean go-task accuracy, however, was found to decrease with time, $F(1) = 5.54$, $p = .019$. The failure to detect a slowing of GoRT and an overall change in mean SSRT over the duration of the experimental task indicated that participants did not adopt a deliberate strategy of waiting for the occurrence of a stop signal, which would have threatened the assumptions of the horse-race model underlying the stop-signal task (Logan & Cowan, 1984).

Developmental Change

Mean scores and standard deviations for performance variables overall, as well as within each of the seven age groups, are presented in Table 1. Factorial ANOVAs with age and gender as between-participant variables revealed no significant gender differences for SSRT or GoRT. Accordingly, only the age variable was included in subsequent analyses of SSRT and GoRT data.

Response Inhibition (Stopping)

One-way ANOVAs revealed a significant overall age effects for SSRT, $F(6, 310) = 13.007$, $p < .001$ (see Figure 1). Significant quadratic ($p < .001$) and linear ($p < .001$) trends for the relationship between SSRT and age group were demonstrated (Table 2).

As evident from the data shown in Table 1, young children (6–8 years) and young adults (18–29 years) were about 80 msec faster than the oldest group of adults (60–82 years). As expected, the planned contrast between young adult (18–29 years) and seniors (60–82 years) was significant, $t(71) = 2.49$, $p < .05$ (two-tailed), $d = .61$, as was the planned contrast between young children (6–8 years) and older children (9–12 years), $t(100) = 2.87$, $p < .001$ (two-tailed), $d = .61$.

Response Execution (Going)

The one-way ANOVA revealed a significant mean effect for age on GoRT, $F(6, 310) = 25.16$, $p < .001$ (see Figure 1). Subsequent trend analyses revealed a significant quadratic relation ($p < .001$) between GoRT and age group (Table 2). Planned comparisons revealed significant differences in GoRT between the

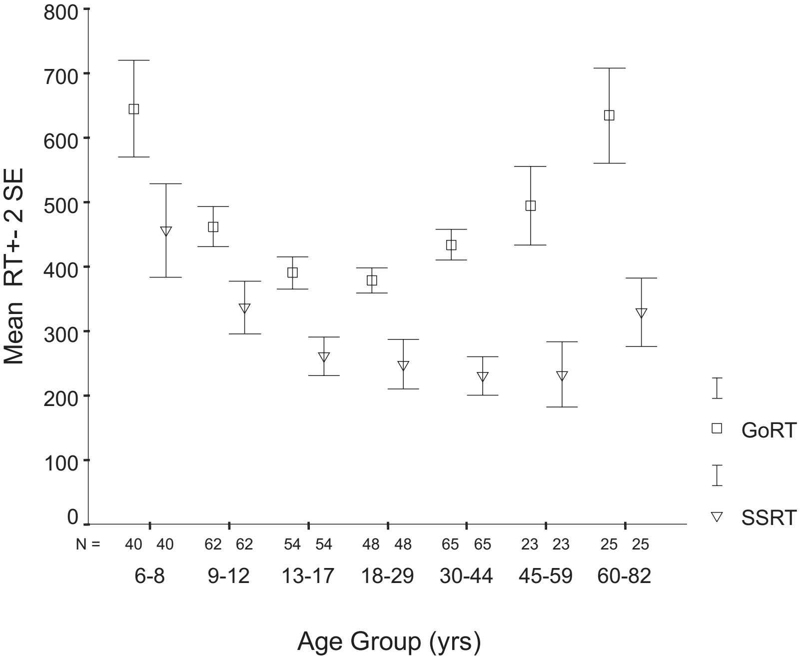

FIGURE 1 Group means (inner symbol) and standard error of the mean (outer bars) for stop-signal reaction time (SSRT) and go-signal reaction time (GoRT) for the seven age groups.

TABLE 2
Trend Analyses of the Relations Between Age and the Primary Dependent Variables

	Trend		
Variable	*Linear F*	*Quadratic F*	*Cubic F*
Stop-signal reaction time	20.49*	43.15*	0.02
Go-signal reaction time	0.37	141.07*	2.59

Note. *df* = 1, 310.
*p < .001.

young adult and older adult groups, $t(71) = 8.45$, $p < .001$ (two-tailed), $d = 1.83$. Specifically, the young adults (18–29 years) were about 250 msec faster than the seniors (60–82 years). These findings indicate that the speed of response execution becomes faster throughout childhood but then slows significantly across the adult years (see Table 1).

Regression Analyses

The results of the regression analyses are summarized in Table 3. Hierarchical multiple regression analysis was used for several reasons. First, two analyses were undertaken to confirm the developmental trends found in SSRT and GoRT (see Table 3, Analyses A and B). The statistical significance of the beta weights (standardized regression coefficients) was interpreted in this respect. For both analyses, age was entered as the first predictor, and on the subsequent step, the quadratic function of age was entered as the second predictor. As expected, the quadratic function of age was a significant predictor of SSRT, $\beta = 1.31$, $t(314) = 6.61$, $p < .001$; and GoRT, $\beta = 1.80$, $t(314) = 9.62$, $p < .001$ (see Figure 2).

We further analyzed the data to determine whether the age-related change in SSRT was distinct from the age-related change in GoRT or whether SSRT changed with age in the same manner as GoRT (Table 3, Analysis C). Accordingly, variables were entered into a regression equation in a hierarchical procedure with SSRT as the dependent variable. GoRT was entered first (to first remove the effect attributable to the speed of responding), followed by age; the quadratic function of age was entered as the last step. This hierarchical approach permitted us to examine the significance of the unique variance added to the equation by the quadratic function of age, over and above that which could be accounted for by GoRT and age (i.e., the significance of the change in explained variance on the final step). After the variance associated with the GoRT and age had been accounted for, the quadratic function of age added a significant amount of unique variance, $R^2\Delta = .11$, $F\Delta\ (1, 313) = 39.21$, $p < .001$.

TABLE 3
Hierarchical Regression Analyses Predicting Stop-Signal Reaction Time and Go-Signal Reaction Time

Analysis and Steps	*Cumulative R*	*F for R*	$R^2\Delta$	$F\Delta$	β	*t for* β
Stop-signal reaction time						
Age	.18	10.86**	.03	10.86**	–1.44	–7.30***
Age^2	.39	28.02***	.11	43.71***	1.31	6.61***
Go-signal reaction time						
Age	.14	5.99*	.02	5.99*	–1.60	–8.55***
Age^2	.49	50.11***	.22	92.49***	1.80	9.62***
Stop-signal reaction time						
Go-signal reaction time	.10	2.85	.01	2.85	–0.06	–0.95
Age	.22	7.90***	.04	12.84***	–1.56	–6.99***
Age^2	.39	18.97***	.11	39.21***	1.41	6.26***

*$p < .05$. **$p < .01$. ***$p < .001$.

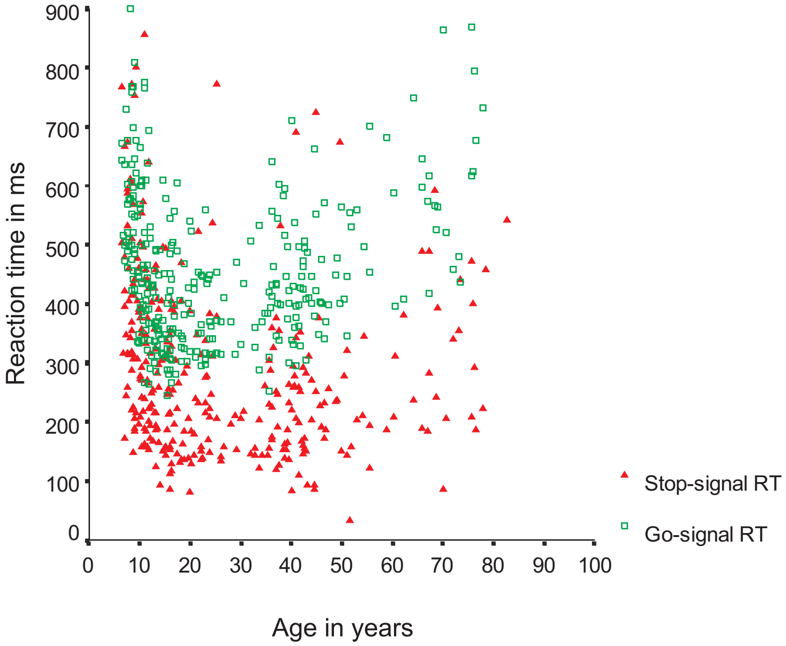

FIGURE 2 Scatter graph of stop-signal reaction time (RT) and go-signal RT as a function of age.

Additional Measures of Performance

One-way ANOVAs among the seven age groups on other outcome measures of the selective stop-signal task also were conducted. The proportion of early (invalid) responses was found to significantly differ among the age groups, $F(6, 310) = 2.28$, $p = .036$. Also, significant differences among the age groups were found in variability of response execution speed, $F(6, 310) = 24.02$, $p = .002$; percentage inhibitory control given the nonselected stop signal, $F(6, 310) = 3.11$, $p = .006$; and overall accuracy of response execution, $F(6, 310) = 13.42$, $p < .001$. Subsequent post hoc analyses revealed that the older adults (>60 years) had a higher overall mean percentage inhibition to the selected tone than all of the other age groups, and that both the youngest (6–8 years) and the oldest (>60 years) age groups had significantly greater variability in GoRT than all of the other age groups. In addition, response execution accuracy increased throughout the life span, with post hoc analyses identifying the children 6 to 12 years old as being significantly less accurate than the adolescents and adults.

DISCUSSION

This study was designed to characterize developmental changes in the ability to selectively inhibit a prepotent course of action. Accordingly, we used a modification of the well-established stop-signal task to measure this type of inhibitory control in a large community sample of individuals ranging in age from 6 to 82 years. The task used in this study was unique from previous versions of the stop-signal task (e.g., Kramer et al., 1994; May & Hasher, 1998; Ridderinkof et al., 1999; Williams et al., 1999) in that we used a choice response execution reaction time task but altered the response inhibition task so that both response execution and response inhibition comprised a fixed choice reaction time task. The central findings are threefold. First, developmental differences in the ability to selectively inhibit prepotent responses were evidenced across the life span. Second, the abilities to selectively inhibit and execute prepotent response followed differential developmental trends. Third, the developmental trends found in selective inhibitory control are unique from those found by others in the inhibition literature.

Results generated from this study indicated that response execution and selective response inhibition follow different developmental trends. Although both SSRT (our primary measure of selective inhibitory control) and GoRT (our primary measure of response execution) improved throughout childhood and diminished throughout adulthood, the developmental trends were less pronounced for the selective inhibition of prepotent responses than for their execution (Figures 1 and 2). We observed a marked difference in the effect size for the relationship between age and response execution (the $R^2\Delta$ indicated that 22% of the variability in GoRT was explained by age) relative to that between age and SSRT (only 11% was explained be age). The contrast observed in the strength of the age effect between response execution and selective response inhibition suggests that the developmental trends may differ.

In addition, the notion of different developmental trends for the two processes is supported by the results of the hierarchical multiple regression analyses, which indicated that the significant age-related change in selective inhibitory control was distinct from the age-related change found in response execution. Specifically, we found that the quadratic function of age was a significant predictor of selective inhibitory control after we accounted for the variance attributable to response execution. That is, after we partialled out any relation between selective inhibitory control and response execution, the pattern of change in selective inhibitory control over the life span still was characterized by a quadratic function ($R^2\Delta = .11$).

The uniqueness in developmental trends for the selective inhibition versus execution of prepotent responses (for both adults and children) supports the underlying theory of the stop-signal task, which posits that the processes governing the inhibition of a speeded response are independent from those governing its execution (Logan, 1994). Evidence of very strong age-related trends for response execution and less pronounced trends for inhibition of the ongoing action provided by this study and previous research (e.g., Band, 1996; Band & van der Molen, 2000; Jennings et al., 1997; Ridderinkof et al., 1999; Schachar & Logan, 1990; Williams et al., 1999) is inconsistent with the hypothesis that speeded information processing is mediated by a single global mechanism (e.g., Cerella & Hale, 1994; Kail, 1993). A number of alternative explanations are possible. First, it is possible that the ability to withhold a planned action is one of the earliest emerging control processes (executive functions) and is also preserved the longest (Barkley, 1997; Welsh & Pennington, 1988). This developmental pattern would make sense from an evolutionary perspective, given the significance of the ability to inhibit for survival. Further investigation of selective inhibitory control and execution of prepotent responses is clearly warranted; such an investigation should extend the study of developmental change into the preschool years and use a longitudinal rather than a cross-sectional design.

A second, perhaps related, explanation for the unique observed developmental trends in selective response inhibition and execution is that the balance between individual differences and developmental differences may vary across cognitive measures. For example, given that the reliabilities of the measures of selective inhibition and response execution were comparable, the difference in strength of the age-related effects suggests that factors other than age are more strongly related to the variance observed in the primary measure of selective inhibition (i.e., SSRT). Perhaps individual differences in selective inhibitory control remain fairly stable across age, whereas individual differences in response execution chance across age. This could not be directly tested in this study but indicates an avenue for further investigation.

Furthermore, due to the nature of the selective stop-signal task, constant cognitive demands on working memory (i.e., having to remember which tone goes with which response) and on set-shifting modalities of differential responses are placed on the participant. Because these cognitive demands have been shown to develop throughout childhood and deteriorate throughout adulthood (e.g., Anderson, Craik, & Naveh-Benjamin, 1998; Chiappe, Hasher, & Siegel, 2000; Kane, Hasher, Stoltzfus, Zachs, & Connelly, 1994) and because they impact more on the inhibitory control process (i.e., having to detect the presence of an auditory tone, discriminating between the pitch of the tones, and finally matching the tone heard to the appropriate response) versus the execution process (i.e., simply matching visually presented stimuli to the appropriate response execution), it is possible that the high impact of the cognitive processes involved in selectively inhibiting responses drives the age-related effects observed.

Although differences in participants prevents us from directly comparing our results with those of other developmental studies that used similar inhibitory tasks, some similarities and differences can be inferred and provide context to this study's findings. Specifically, Kramer et al (1994), May and Hasher (1998), and this study demonstrated a more marked slowing of SSRT in later adulthood than shown by Williams et al. (1999). We should note that the response execution tasks used by Kramer et al. and May and Hasher were more complicated than that used by Williams et al. That is, Kramer et al.'s response execution task included a response compatibility component, and May and Hasher required the participant to judge whether an item (e.g., chair) was a member of a particular category (e.g., furniture). In comparison, the response execution task used by Williams et al. only required that the participant respond to the letters *X* and *O* and attempt to inhibit responding whenever an auditory stop-signal was presented. Our study was unique in design from all three of these studies in that we used a different response inhibition (i.e., stop) task. That is, we required participants to discriminate between the selected stop-signal tone and another similar auditory stop-signal tone while executing a response. This was more complicated than the Williams et al. response inhibition task that presented only one possible auditory stop-signal tone and required the cessation of response execution whenever a stop-signal tone was presented. The overall increase in cognitive demands in this study and in those by Kramer et al. and May and Hasher may have caused greater difficulty in controlling the inhibition process, particularly in the elderly.

We found evidence of strong developmental trends throughout the life span for the execution of prepotent responses. That is, response execution speed (GoRT) increased throughout childhood and then gradually decreased (slowed) throughout adulthood, resulting in a marked U-shaped function (Figure 1). These findings are consistent not only with previous studies that used the stop-signal task (Band & van der Molen, 2000; Ridderinkof et al., 1999; Williams et al., 1999) but with a substantial body of literature demonstrating developmental improvement in response speed in childhood and progressive slowing through adulthood on a wide variety of speeded response tasks (Cerella, 1990; Kail, 1991, 1993).

Future studies on the development of selective inhibitory control compared with other types of inhibitory control are clearly warranted. For instance, a direct comparison of selective inhibitory control as measured by the selective stop-signal task versus nonselective (stop-all) inhibitory control, or a comparison of selective inhibitory control as defined perceptually in this study (i.e., requiring the discrimination between auditory tones) versus motor-based selective inhibitory control (i.e., requiring the selection of the appropriate motoric response), would enhance our understanding of this complex cognitive process.

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