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Development of Inhibitory Control Across the Life Span

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The stop-signal procedure was used to examine the development of inhibitory control. A group of 275 participants, 6 to 81 years of age, performed a visual choice reaction time (go) task and attempted to inhibit their responses to the go task when they heard a stop signal. Reaction times to the stop and go signals were used to assess performance in inhibition and response execution, respectively. Results indicated the speed of stopping becomes faster with increasing age throughout childhood, with limited evidence of slowing across adulthood. By contrast, strong evidence was obtained for age-related speeding of go-signal reaction time throughout childhood, followed by marked slowing throughout adulthood. Hierarchical regression confirmed that the age-related change in inhibitory control could not be explained by general speeding or slowing of responses. Findings are discussed in regard to the contrast between the development of inhibition and response execution and the utility of the stop-signal procedure.

The concept of inhibition is central to theories of development and aging that interpret cognitive difficulties of young children and elderly people as deficits in inhibitory processing (e.g., Bjorklund & Harnishfeger, 1990; Hasher & Zacks, 1989; Kramer, Humphrey, Larish, & Logan, 1994). Moreover, deficient inhibition is central to current theories of psychopathology (e.g., Barkley, 1997; Gray, 1987; Patterson & Newman, 1993; Quay, 1997). The general concept of inhibition appears in many different guises and is measured in a variety of ways in many different literatures (e.g., Dagenbach & Carr, 1994; Kramer et al., 1994). The present article focuses on the type of inhibition that is manifest in the *stop-signal procedure* (Lappin & Eriksen, 1966; Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984; Ollman, 1973; Osman, Kornblum, & Meyer, 1986, 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).

Stop-signal inhibition is distinguished from other types of inhibition in several ways: (a) It requires the individual to take a deliberate action (i.e., stop an already-initiated speeded voluntary response); (b) it represents an entire cognitive process extending from stimulus (stop signal) to response (an internal inhibitory response); (c) the inhibitory process is largely independent of the excitatory or "go" process, against which it races; and (d) it is based on a formal theory of the stopping process (see Logan, 1994, for a more detailed discussion). The stop-signal procedure is a laboratory analogue of a situation that requires an individual to stop a planned or prepotent response. It involves two concurrent tasks, a go task and a stop task. The go task is typically a choice reaction time task that requires individuals to discriminate between an *X* and an *O*, responding quickly and accurately to that imperative go signal. The stop task, which occurs randomly and infrequently (e.g., 25% of go-task trials), involves presentation of a tone (stop signal) that countermands the go signal by instructing the individual to inhibit his or her planned response to the go task on that trial. According to the underlying theory (Logan & Cowan, 1984), the individual's ability to inhibit is dependent on the outcome of a race between the two independent processes responsible for the production and stopping of the response, respectively. If the

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inhibition process wins the race, the ongoing action is stopped; however, if the response execution process wins, the response to the go task continues much as would have occurred had no stop signal been presented. Thus, inhibitory control depends on the latency of the response to the go signal (*go-signal reaction time*) and the latency of the response to the stop signal (*stop-signal reaction time*). Poor inhibitory control could result from responding too fast to the go signal (i.e., fast responses would be executed before the individual could respond to the stop signal) or too slow to the stop signal (which would allow normally paced responses to the go task to escape inhibition).

The advantages of the stop-signal procedure and underlying model are numerous. In contrast to neuropsychological measures of this type of inhibition (e.g., the Matching Familiar Figures Test; Kagan, Rosman, Day, Albert, & Philips, 1964), the stop-signal procedure allows more precise measurement of the underlying processes involved (e.g., Logan, 1994; Logan & Cowan, 1984; Schachar & Logan, 1990; Schachar & Tannock, 1995). The procedure allows for a clear definition of the conditions that trigger the act of control (i.e., presentation of the stop signal) and the changes that result from executing the act (i.e., inhibition of the response). That is, the stop-signal procedure involves presenting the participant with a signal to inhibit responding and specifically examines the response to that signal. Also, the model provides a way of measuring the latency of the internally generated act of control (stop-signal reaction time) even though successful inhibition produces no overt behavior. Stop-signal reaction time is the primary performance variable and indicates the speed of the inhibition process. Stop-signal reaction time does not provide all of the information yielded by the stop-signal procedure; it is highly informative, however, because changes in stop-signal reaction time characterize important differences between groups of individuals (e.g., impulsive adults have longer stop-signal reaction times than nonimpulsive adults; Logan, Schachar, & Tannock, 1997) and individuals tested under different conditions (e.g., stimulant medication improves stop-signal reaction time in comparison with placebo in children with attention deficit hyperactivity disorder; Tannock, Schachar, Carr, Chajczyk, & Logan, 1989; Tannock, Schachar, & Logan, 1995). Moreover, the stop-signal procedure provides a way of measuring inhibition (stop-signal reaction time) that controls for any concurrent differences in speed of responding to the go signal (go-signal reaction time). This is important because slower response execution processes are easier to stop than faster ones at equivalent stop-signal delays (Logan, 1994). Because development may affect the speed of response execution processes, the ability to disentangle the effects of the response execution processes on the inhibition processes is of utmost importance.

Developmental change in the speed of responding has been well documented in a wide variety of reaction time tasks (e.g., Cerella & Hale, 1994; Hale, 1990; Kail, 1993). Response speed increases throughout childhood, reaches a peak in early adulthood, and then decreases gradually throughout adulthood (Hale, 1990). The consistency of the age-related improvements in response speed across a variety of different tasks has given rise to a hypothesis of a global mechanism that influences the speed of information processing (Kail, 1993). By contrast, developmental change in inhibitory control is unclear. Not only are there fewer studies, but those available yield only limited evidence of age-related speeding of response inhibition processes throughout childhood (Band, 1996; Jennings, Van der Molen, Pelham, Debski, & Hoza, 1997; Oosterlaan, 1996; Schachar & Logan, 1990) and of age-related slowing across adulthood (Kramer et al., 1994). Confirmation that development of inhibitory control follows a time course different from that of response processes would challenge the notion of a global mechanism that underlies all age-related changes in component processes.

It is not surprising that the evidence for developmental change in inhibitory control is equivocal. No study to date has examined this construct across the entire life span, and in some cases modest samples threaten the integrity of the findings. Accordingly, the goal of the current study was to provide a more stringent investigation of developmental change in inhibitory control by using the same paradigm (stop-signal procedure) with a wider age range (i.e., 6 to 81 years) and a larger sample from the normal population to afford adequate statistical power. We expected that developmental change in inhibitory control would parallel that of response execution. Specifically, we predicted that the speed of the inhibitory process would become faster (and therefore more effective) throughout childhood and then become slower (and therefore less effective) throughout adulthood. An alternative hypothesis is that inhibitory control develops by a different time course than response execution processes.

Method

Participants

During a 2-week period in the summer of 1996, 284 visitors to the Ontario Science Centre were recruited on a volunteer basis. Of these individuals, 9 (3%) were eliminated because of extreme scores (3 or more standard deviations from the mean) on the two primary outcome variables (5 for stop-signal reaction time and 4 for go-signal reaction time), leaving data from 275 participants to be used for analyses. The study design was not adapted for special needs; thus, volunteers with vision, hearing, or motor function impairments and those who did not speak at least some English or French were not eligible to participate. There were no family relationships between any of the participants.

The participants ranged in age from 6 to 81 years. One hundred thirty-five participants were male, and 136 were female (gender data were missing for 4 participants). Moreover, as shown in Table 1, gender distribution across the seven age groups was fairly uniform. As might be expected, the majority of participants had a strong educational background: Virtually all of the participants less than 17 years of age were attending school; 30% of the young adults had completed secondary school, and 55% were completing some postsecondary education; and a majority of the adults had completed some postsecondary education (70% of the midadult group, 85% of the older adult group, and 71% of the seniors). Information on ethnicity was not collected, but the Ontario Science Centre attracts visitors from the United States, Europe, Asia, and Australia, as well as from Canada. Accordingly, a wide range of ethnic groups were represented in the sample.

Apparatus and Stimuli

The stimuli for the stop-signal procedure were presented on four stand-alone desktop computers (IBM-compatible), each equipped with size-adjustable padded headphones through which an auditory signal could be presented without the hindrance of background noise. Mesh screens were installed on the computer monitors to reduce glare. Each computer was also equipped with a handheld response box (14 cm × 8.5 cm × 3.5 cm) that

Table 1

Description of Age Groups and Related Means for Critical Measures From the Stop-Signal Procedure

Age group	Age (years)	Description	*n*	Female (%)	SSRT		GoRT		*SD* GoRT		P(I/S)		Correct (%)[a]		Split-half reliability	
					M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	SSRT	GoRT
1	6–8	Early childhood	29	41	274.0	69.8	674.8	114.6	205.6	53.9	49.7	3.1	94.8	4.0	.56	.91
2	9–12	Midchildhood	41	46	223.0	75.3	503.7	96.2	128.1	32.0	49.5	4.9	95.9	4.3	.86	.97
3	13–17	Adolescence	50	38	197.7	75.9	393.7	63.1	91.2	21.5	50.0	2.4	96.8	3.5	.91	.93
4	18–29	Young adulthood	47	60	208.6	75.1	361.8	67.0	78.9	22.5	49.5	2.8	97.6	3.4	.91	.97
5	30–44	Midadulthood	55	54	209.7	63.1	401.0	80.6	83.7	24.3	50.2	2.9	98.4	2.0	.90	.97
6	45–59	Older adulthood	28	54	212.6	65.5	439.3	73.6	92.0	37.3	50.4	2.4	99.1	1.0	.95	.98
7	60–81	Elderly	25	60	230.1	67.2	537.7	121.9	110.2	25.0	51.3	2.9	98.6	2.0	.83	.97
Total	6–81		275	50	218.3	73.2	453.5	127.1	107.0	48.3	50.0	3.2	97.3	3.4	.86	.98

Note. Mean stop-signal delay may be calculated from the data presented, because SSRT = GoRT − delay (see Appendix); it follows that delay = GoRT − SSRT. SSRT = stop-signal reaction time (ms); GoRT = go-signal reaction time (ms); P(I/S) = probability of inhibition given a stop signal.
[a] Accuracy of go-task responding expressed as percentage of correct go-signal responses.

contained three single-pole double-throw buttons. The buttons were arranged in a line through the center of the top of the box, and the two outermost buttons were labeled with either an *X* or an *O*.

The stimuli for the go task were the uppercase letters *X* and *O*, presented in the center of the screen for 1,000 ms. Each go-task stimulus was preceded by a 500-ms fixation point, also presented in the center of the screen. The stop signal was a 100-ms, 1000-Hz tone generated by the computer and delivered through headphones at a comfortable volume for listening. The stop-signal delay (the interval between the presentation of the go signal and the stop signal) was changed dynamically after every stop-signal trial according to the participant's performance (Logan et al., 1997). Stop-signal delay was set at 250 ms initially and then adjusted in the following manner. The delay increased by 50 ms if the participant inhibited successfully (making it harder to inhibit on the next stop-signal trial) and decreased by 50 ms if the participant failed to inhibit (making it easier to inhibit on the next stop-signal trial). This on-line tracking system was designed to force a "tie" finish between go-task responding and stop-task responding. Thus, the goal of the tracking algorithm was to allow participants to inhibit the go task on only 50% of the stop-signal trials, as was necessary for the estimation of stop-signal reaction time (see the Appendix). This tracking procedure compensated for individual (and group) differences in go-signal reaction time. Computer simulations of various methods used to estimate stop-signal reaction time indicate that estimates based on this tracking algorithm are robust against a number of influences (e.g., the assumption of independence between the speed of the response process and the stop process; for reviews, see Band, 1996; Logan, 1994). A more detailed exposition of the conceptual and mathematical model has been presented previously (e.g., Logan, 1994; Logan & Cowan, 1984).

The experimental task comprised 256 trials divided into eight 32-trial blocks. There were an equal number of *X*s and *O*s in each block. The stop signal was presented on 25% of go-signal trials (distributed randomly in each block of 32 trials), 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 1 trial every 2.5 s.

Two questionnaires were administered. One comprised 14 items that elicited information about age, gender, educational level, learning difficulties, health, accident history, and current prescribed medications. The other consisted of two subscales (Venturesomeness and Impulsiveness) of the Impulsiveness Questionnaire (Eysenck, Pearson, Easting, & Allsopp, 1985). The Junior I-6 version (Eysenck, Easting, & Pearson, 1984), which consists of 46 true–false items (23 impulsivity items and 23 venturesomeness items), was used for participants less than 16 years of age, whereas the I-7 version (Eysenck et al., 1985), which comprises 35 true–false items (19 impulsivity items and 16 venturesomeness items), was used for participants more than 16 years of age. The items were presented in a list format, with impulsivity and venturesomeness items intermixed. Some questions were worded negatively to control for acquiescence bias. Data from these questionnaires are not included in the current article (they will be presented in a subsequent report).

Procedure

Located within a neurosciences exhibit at the Ontario Science Centre, the testing area was enclosed and divided into two rooms: one for completion of the questionnaires and the other for completion of the stop-signal procedure. Each participant signed a consent form and completed the general information and personality questionnaires in the first testing room. Questionnaires for child participants were completed by an accompanying parent or guardian. The questionnaires took approximately 10 min to complete.

The stop-signal procedure was administered to each participant individually. Each participant was accompanied at the terminal by a researcher who read a uniform set of instructions, operated the computer, and monitored the participant's progress until completion of the computer task. A maximum of 4 participants could be tested at any given time, and each administration of the stop-signal procedure lasted approximately 20 min.

Each participant completed two practice blocks before commencing the eight test blocks. In the first practice block of 32 trials, participants focused on the go task only. Participants were told that they would see a fixation point followed by a letter 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 occasionally an auditory tone would be presented (so that they could become accustomed to it), but they were to ignore it during this practice block. In the second practice block (32 trials), the stop task was described. Participants were told that they were to continue responding to the letters as quickly and accurately as possible but that now, when they heard the tone, they were to try to stop responding on that trial. They were encouraged to inhibit their responses if they could but not to worry if they were unable to do so. The stop signal would occur at different times; thus, sometimes they would be able to stop, but other times they would not. Also, they were instructed not to wait for the stop signal, because it occurred randomly and infrequently. The stop-signal delay was set at 250 ms and then adjusted dynamically in 50-ms steps according to the participant's inhibitory performance (as described previously).

After completion of the practice blocks, the stop-signal delay was reset to 250 ms before the start of the first test block. The program was paused twice during the experimental trials (after Blocks 3 and 6) to allow participants to rest and to display the mean go-signal reaction time on the screen for the blocks preceding the pause. This visual feedback allowed the supervising researcher to monitor go-task performance and reiterate instructions so that participants would maintain a relatively consistent go-signal reaction time throughout the task and not slow down in an attempt to increase the chance of stopping.

Data were saved by each computer as the task ran. The program registered go-signal reaction time and estimated stop-signal reaction time using the method outlined in the Appendix. In addition, two other variables were recorded for each participant: the accuracy of go-task responding and the probability of inhibiting go-task responding given a stop signal. Data from the first test block were excluded from all analyses because the tracking algorithm required a few trials to adjust to individual participants.

Statistical Analysis

The data were analyzed in several stages. First, participants were separated into seven age groups according to stage in the life cycle and the demand to construct groups of relatively equal size that also afforded a comparison with data from previous studies (e.g., Kramer et al., 1994; Schachar & Logan, 1990). The construction of seven age groups (vs. two to four groups in previous studies) afforded a more refined resolution of developmental change than available to date. Next, we conducted a reliability check of the data obtained with the stop-signal procedure by computing split-half reliability coefficients and examining stability of performance across the task (first half vs. second half). Then an analysis of variance (ANOVA) approach was used to determine the effects of age and gender on inhibition and execution of prepotent responses (using stop-signal reaction time and go-signal reaction time as dependent variables, respectively). This was followed by a trend analysis testing the hypothesis that each of the criterion variables (stop-signal reaction time and go-signal reaction time) would have a curvilinear (quadratic) relationship with age. Planned contrasts were also performed to allow examination of the differences in stop-signal reaction time previously reported between specific age groups in childhood (Schachar & Logan, 1990) and adulthood (Kramer et al., 1994). Finally, data were examined via a hierarchical regression approach to confirm the curvilinear relationships observed between age and each of the two criterion variables and to compare developmental trends.

Results

Reliability Check

Split-half reliability coefficients were computed for the main dependent variables (stop-signal reaction time and go-signal reaction time) by correlating data from odd and even blocks (excluding the first block, as stated previously) for the entire sample and for each age group separately. The results are summarized in the last two columns of Table 1. With the exception of the stop-signal reaction time coefficients for the youngest group (6–8 years), the coefficients were consistently positive and high. When data from the 6-year-olds were excluded, the correlation for the 7–8-year-old group was strengthened (r = .83), suggesting that the stop-signal procedure is robust across a wide age range but that modifications may be required for children younger than 7 years of age.

As evident from the data in Table 1, participants of all ages performed with proficiency in regard to correct responding to go signals: The mean accuracy of response was 97.3% (SD = 3.4%). Also, the mean probability of inhibiting go-task responding given a stop signal was 50% (SD = 3.2%), indicating that the tracking method was robust across age in its design to "tie" the race between the processes involved in producing and stopping the response (i.e., inhibit 50% of stop-signal trials).

Also, repeated measures ANOVAs across test blocks (Blocks 2–4 vs. Blocks 5–8) were conducted to examine the effects of time on task on the two criterion variables (stop-signal reaction time and go-signal reaction time). These analyses confirmed that there was no impact of time on task on stop-signal reaction time but that go-signal reaction time was significantly faster for all age groups during the last part of the task than during the first part, $F(1, 268) = 24.53, p < .0001$. On average, go-signal reaction time for the last part of the task (Blocks 5–8) was 19 ms faster than for the first part (Blocks 2–4). The findings for go-signal reaction time indicate that participants did not adopt a deliberate strategy of waiting for the occurrence of the stop signal, which would have posed a threat to the assumptions of the horse-race model (e.g., Logan & Cowan, 1984).

Developmental Change

Means and standard deviations for all variables for each of the seven age groups are presented in Table 1. Factorial ANOVAs with age and sex as between-subjects variables revealed no significant sex differences for stop-signal reaction time. Accordingly, only the variable of age was included in subsequent analyses of stop-signal reaction time data. One-way ANOVAs revealed a significant overall age effect for stop-signal reaction time, $F(6, 268) = 4.14, p < .001, \eta^2 = .09$ (see Figure 1). As shown in Table 2, both the linear and quadratic trends for age were significant. As evident from the data shown in Table 1, young children (6–8 years) were approximately 50 ms slower in stopping than older children (9–12 years), and young adults (18–29 years) were about 20 ms faster than the oldest group of adults (60–81 years). As expected, the planned comparison between the early childhood group (6–8 years) and the midchildhood group (9–12 years) was significant, $t(268) = 2.97, p < .01$, indicating marked development in speed of stopping across childhood. Conversely (and contrary to expectations), the planned contrast between young adults (18–29 years) and seniors (60–81 years) was not significant, $t(268) = 1.23, p > .1$.

A factorial ANOVA conducted for go-signal reaction time revealed a statistically significant main effect for sex indicating that female participants ($M = 468.85, SD = 130.26$) were slower to respond than male participants ($M = 439.62, SD = 123.00$), $F(1, 258) = 5.78, p < .05, \eta^2 = .01$. Because the practical significance of the effect was minimal, only the variable of age was used in subsequent analyses of data for go-signal reaction time, collapsing across the gender variable. The one-way ANOVA revealed a significant main effect for age, $F(6, 268) = 54.50, p < .001, \eta^2 = .55$ (see Figure 1). Trend analysis revealed significant effects for the linear, quadratic, and cubic functions between go-signal reaction time and age (see Table 2). Planned comparisons revealed significant differences in go-signal reaction time between the early childhood and midchildhood groups, $t(53.6) = 6.57, p < .001$, and between the young adulthood and older adulthood groups, $t(31.9) = 6.70, p < .001$.[1] Whereas the youngest children (6–8

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[1] Separate variance estimates were used for the planned comparisons because of unequal variances.

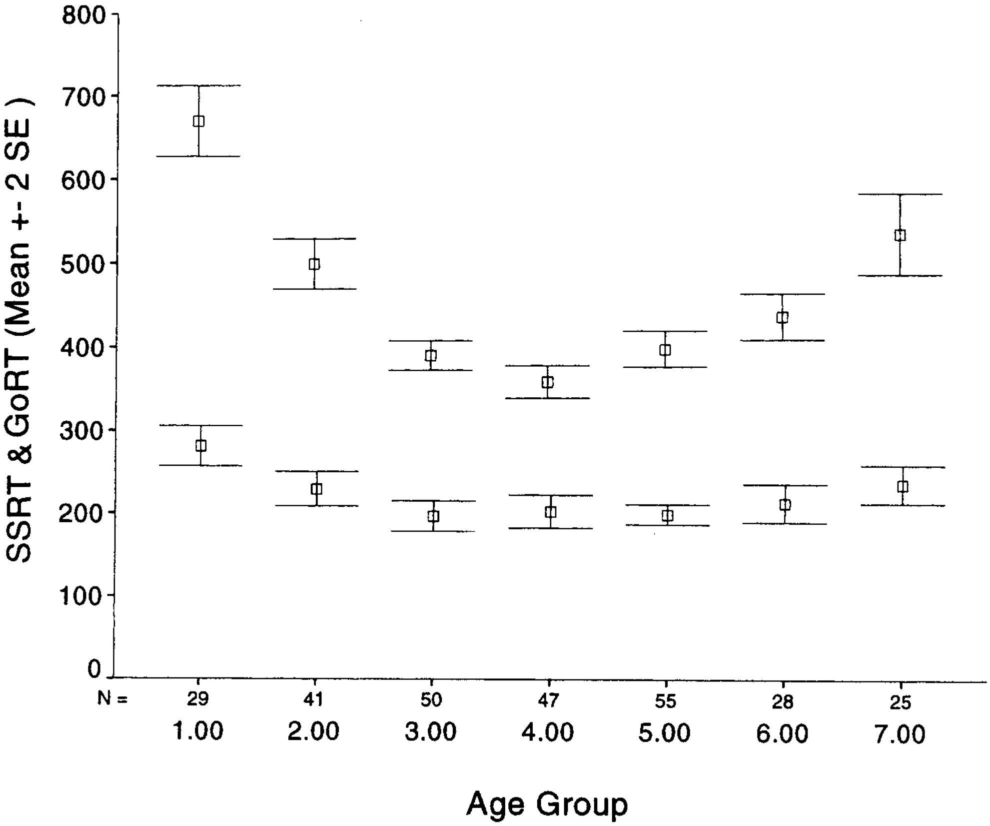

Figure 1. Group means (inner symbol) and standard errors of the mean (outer bars) for stop-signal reaction time (SSRT) and go-signal reaction time (GoRT) for seven age groups.

years) were 170 ms slower in go-signal reaction time than the older children (9–12 years), the young adults (18–29 years) were about 175 ms faster than the seniors (60–81 years). These findings indicate that the speed of responding to go signals becomes faster throughout childhood but then slows across the adult years (see Table 1).

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 stop-signal reaction time and go-signal reaction time (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 stop-signal reaction time, $\beta = 0.72$, $t(272) = 3.09$, $p < .01$, and go-signal reaction time, $\beta = 2.11$, $t(272) = 10.53$, $p < .001$ (see Figure 2).

Second, further analysis of the data was conducted to determine whether the age-related change in stop-signal reaction time was distinct from the age-related change in go-signal reaction time or whether stop-signal reaction time changed with age in the same manner as go-signal reaction time (Table 3, Analysis C). Accordingly, variables were entered into a regression equation in a hierarchical procedure with stop-signal reaction time as the dependent variable. Go-signal reaction time was entered first (to first remove the effects attributable to the speed of responding), followed by age; the quadratic function of age was entered as the last step. This hierarchical approach permitted an examination of 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 go-signal reaction time and age (i.e., the significance of the change in explained variance on the final step). After the variance associated with go-signal reaction time and age had been accounted for, the quadratic function of age added a significant

Table 2
Trend Analysis of the Relationship Between Age and the Primary Dependent Variables

Variable	Trend Linear (*F*)	 Quadratic (*F*)	 Cubic (*F*)
Stop-signal reaction time	3.91*	16.63***	3.07
Go-signal reaction time	49.06***	269.14***	6.72*

Note. $df = 1, 268$.
$^{*}p < .05$. $^{***}p < .001$.

Table 3
Hierarchical Regression Analyses Predicting Stop-Signal Reaction Time (SSRT) and Go-Signal Reaction Time (GoRT)

Analysis and step	Cumulative R	F for R	(df)	ΔR^2	ΔF	(df)	β	t for β	(df)
A. SSRT									
Age	.05	0.80	(1, 273)	.00	0.80	(1, 273)	−0.05	0.89	(273)
Age squared	.19	5.20**	(2, 272)	.03	9.57**	(1, 272)	0.72	3.09**	(272)
B. GoRT									
Age	.07	1.43	(1, 273)	.01	1.43	(1, 273)	−0.07	1.20	(273)
Age squared	.54	56.48***	(2, 272)	.28	110.95***	(1, 272)	2.11	10.53***	(272)
C. SSRT									
GoRT	.10	2.79	(1, 273)	.01	2.79	(1, 273)	0.10	1.67	(273)
Age	.11	1.70	(2, 272)	.00	0.61	(1, 272)	−0.05	0.78	(272)
Age squared	.19	3.45*	(3, 271)	.02	6.89**	(1, 271)	0.73	2.63**	(271)
D. SSRT: Ages 6–17, n = 120 (speeding)									
GoRT	.27	9.37**	(1, 118)	.07	9.37**	(1, 118)	0.27	3.06**	(118)
Age	.40	10.86***	(2, 117)	.08	11.52**	(1, 117)	−0.44	3.39**	(117)
E. SSRT: Ages 18–81, n = 155 (slowing)									
GoRT	.16	4.04*	(1, 153)	.03	4.04*	(1, 153)	−0.16	2.01*	(153)
Age	.27	6.03**	(2, 152)	.05	7.83**	(1, 152)	0.27	2.80**	(152)

Note. Analyses involved the entire sample (ages 6–81; N = 275) unless otherwise specified.
$^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

amount of unique variance (albeit very small), $\Delta R^2 = .02$, $F(1, 271) = 6.89$, $p < .01$.

Because a statistically significant portion of the age-related change in stop-signal reaction time was distinct from the age-related change in go-signal reaction time over the life span, additional analyses were conducted to examine whether this effect was specific to speeding (across childhood) or slowing (across adulthood; Table 3, Analyses D and E). By collapsing the seven ANOVA groups into two groups, it was possible to repeat the latter hierarchical regression separately for children (6–17 years) and adults (18–81 years). Although the quadratic function of age was a predictor of stop-signal reaction time across the life span, age was expected to have a linear relationship with this variable when analyzed separately in children and adults. As such, go-signal reaction time was entered as the first predictor of stop-signal reaction time, followed by only one step in which age was entered. Consistent with the previous model, the change in variance explained from the first to the second step was examined for statistical significance. This analysis was performed twice, once in children and once in adults. After the variance associated with go-signal reaction time had been accounted for, age added a significant portion of unique variance for both children, $\Delta R^2 = .08$, $F(1, 117) = 11.52$, $p < .01$, and adults, $\Delta R^2 = .05$, $F(1, 152) = 7.83$, $p < .01$ (Table 3).

Discussion

The present study was designed to characterize developmental changes across the life span in the ability to inhibit a prepotent course of action. Accordingly, we used the stop-signal procedure to measure this type of inhibitory control in a large community sample of individuals 6 to 81 years of age. The central findings are

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

that the ability to inhibit prepotent responses improved throughout childhood and then diminished slightly throughout adulthood, whereas the ability to execute prepotent responses not only improved throughout childhood but also declined throughout adulthood (as reflected by age-related changes in stop-signal reaction time and go-signal reaction time, respectively). Moreover, the developmental trends were less pronounced for inhibition of prepotent responses than for their execution, suggesting that the underlying processes may follow different developmental time courses. Also, findings from the present study demonstrate the robustness of the stop-signal procedure for measuring inhibitory control across the life span.

The age-related changes in stop-signal reaction time provide evidence of significant improvements in the ability to inhibit a prepotent course of action throughout childhood but little change throughout adulthood. On average, older children (9–12 years; mean age = 11.1 years) were about 50 ms faster in stopping their prepotent responses to the go task than were younger children (6–8 years; mean age = 7.5 years). By contrast, older adults (60–81 years) were surprisingly fast at stopping relative to young adults (18–29 years); these older adults were only about 20 ms slower.

Our finding of developmental improvements in inhibitory control in childhood stands in apparent contradistinction with previous studies that failed to detect significant developmental change throughout this age range (e.g., Band, 1996; Jennings et al., 1997; Oosterlaan & Sergeant, 1997; Schachar & Logan, 1990). However, inspection of the mean values reported in those studies indicated that the observed difference in stop-signal reaction time for younger versus older children was similar in magnitude to that obtained in the present study. For example, in the study by Schachar and Logan (1990), children in Grade 4 (mean age = 9.8 years) were about 50 ms faster in stopping than those in Grade 2 (mean age = 7.9 years). Also, Band (1996) found that 11-year-olds were about 40 ms faster in stopping than were 8-year-olds. Moreover, using a tracking procedure similar to that used in the present study, Band (1996) obtained stop-signal reaction times (8-year-olds: 280 ms; 11-year-olds: 241 ms) that were comparable to those obtained in the present study (see Table 1). These observations suggest that small sample size and resultant low statistical power in the previous studies relative to the present study most likely account for the inconsistent findings for development of inhibitory control in childhood.

On the other hand, the discrepancy between our findings for the effects of aging on inhibitory control and those of Kramer and colleagues (Kramer et al., 1994) is not readily attributable to differences in age range or sample size. Specifically, those investigators demonstrated a more marked slowing of stop-signal reaction time throughout adulthood than shown in the present study (by an average of 90 ms vs. 20 ms). It should be noted that the go task used by Kramer et al. was more complicated than that used in the present study (i.e., it included a response compatibility component). The overall increase in cognitive demands may have given rise to greater difficulty in controlling the stopping process, particularly in elderly people.

By contrast to the relatively limited developmental change in inhibition of prepotent responses, we found evidence of strong developmental trends throughout the life span for execution of these responses. That is, speed of responding to the go task increased throughout childhood and then gradually decreased (slowed) throughout adulthood, resulting in a U-shaped function. These findings are consistent not only with previous studies using the stop-signal procedure but with a substantial body of literature demonstrating developmental improvement in response speed in childhood and progressive slowing throughout adulthood on a wide variety of speeded response tasks (Cerella, 1990; Kail, 1991, 1993).

Essential to an understanding of the development of inhibitory control is a consideration of the apparent diversity in the observed pattern of age-related changes in the inhibition and execution of prepotent responses: specifically, how the pattern may relate to theoretical frameworks suggested to explain inhibitory control and developmental changes in the ability to inhibit or execute speeded responses. Before we embark on that discussion, several comments are warranted. First, we observed a marked difference in the effect size for the relationship between age and response execution (the ΔR^2 indicates that 28% of the variability in go-signal reaction time was explained by age) relative to that between age and inhibition (only 3% of the variability was explained by age). The contrast observed in the strength of the age effect between response execution and inhibition suggests that the developmental trends may differ.

Second, the notion of different developmental trends for the two processes is supported by the results of the hierarchical multiple regression analysis, which indicated significant age-related change in inhibition distinct from age-related change in response execution. Specifically, we found that the quadratic function of age was a significant predictor of inhibition after accounting for the variance attributable to response execution. That is, after partialing out any relationship between inhibition and response execution, the pattern of change in inhibition over the life span was still characterized by a quadratic function, although the amount of unique variance was extremely small ($\Delta R^2 = .02$), albeit statistically significant.

Finally, we found that the unique relationship between age and inhibition was not restricted to the speeding component (through childhood) of the inhibition curve. Rather, age was a significant predictor of inhibition in both children and adults (when analyzed separately) after the variance attributable to response execution had been accounted for (see Table 3). However, the addition of age into the regression equation in children resulted in a larger change in the proportion of shared variance than in adults. That is, for both children and adults, there was significant age-related change in inhibition that was distinct from age-related change in response execution, but this effect was stronger in children.

The diversity in developmental trends for inhibition versus execution of prepotent responses (for both adults and children) lends support to the underlying theory of the stop-signal procedure, 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 the inhibition of the ongoing action provided by the current study and in previous research (e.g., Band, 1996; Jennings et al., 1997; Schachar & Logan, 1990) is inconsistent with the hypothesis that speeded information processing is mediated by a single global mechanism (e.g., Cerella, 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 one that is also preserved the longest (Barkley, 1997; Welsh & Pennington, 1988). This developmental pattern would make sense from an evolutionary perspective, given the significance of inhibitory control for survival. Further investigation of inhibition and execution of prepotent responses is clearly warranted, extending the study of developmental change into the preschool years and using a longitudinal rather than cross-sectional design.

A second, perhaps related explanation is that the balance between individual differences and developmental differences may vary across cognitive measures. For example, given that the reliability of the measures of inhibition and response execution was comparable, the difference in strength of the age-related effects suggests that factors other than age are more strongly related to variance in the inhibition measure. One possible factor is that of individual differences in inhibitory control, which are fairly stable across age, whereas individual differences in response inhibition change across age. This could not be directly tested in the current study but indicates an avenue for further investigation.

A third possible explanation of the difference in strength between age-related effects on inhibition and response execution implicates personality. Traits associated with age, such as venturesomeness, might enhance the response execution curve (i.e., reckless youths may "go" faster than cautious seniors). Conversely, dispositions acting on inhibitory processes may be independent of age, thus complicating the developmental effect. For example, impulsive individuals may demonstrate deficits in inhibitory control regardless of age. Impulsivity has been demonstrated to be significantly related to inhibition processes but not response execution processes (Logan et al., 1997), and much of the research linking inhibitory control to psychopathology has focused on the impulsive component of attention deficit hyperactivity disorder (Schachar, Tannock, & Logan, 1993).

Finally, the results of the present study indicate that the stop-signal procedure provides a robust measure of inhibitory control across a wide age span. Participants from primary school age through senior citizenship, both female and male, were able to complete the task, respond to go signals with high levels of accuracy, and inhibit their prepotent response to the extent predicted by the tracking procedure used to adjust stop-signal delays (i.e., 50%). Our interpretation of data from the small sample of 6-year-olds is that modifications may be required for children younger than approximately 7 years of age (e.g., more practice, shorter task duration, and increased frequency and saliency of feedback on performance). Notwithstanding the preceding cautionary note, the life span data provided by our study may serve as a reference base for applied research examining neuropsychology and psychopathology (e.g., to test models and theories proposed to explain cognitive aging or various disorders such as Parkinson's disease, Alzheimer's disease, schizophrenia, and attention deficit hyperactivity disorder).

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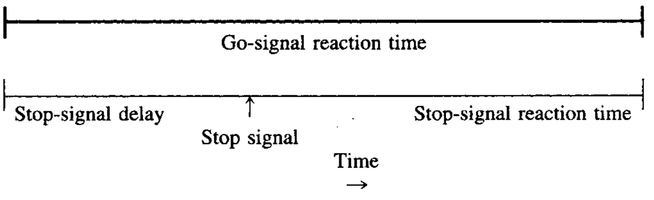
Appendix

Tracking Algorithm

Unlike go-signal reaction time, the speed of stopping (stop-signal reaction time) cannot be measured directly; however, the race model provides a way of estimating this variable. Whether or not participants are able to inhibit their response depends on a race between the response execution process (go-task response) and the inhibition process (stop-task response); if participants finish the stop task before the go task, they inhibit their response to the go task. However, if they finish the go task before the stop task, they fail to inhibit their response to the go task, responding much as they would had no stop signal been presented.

Researchers vary the interval between the go signal and the stop signal (stop-signal delay) to "handicap" the race in favor of one process or the other. In the current method, we used a tracking procedure in which stop-signal delay changes after every stop-signal trial, increasing by 50 ms if participants stop their response and decreasing by 50 ms if they respond (i.e., fail to inhibit their response). This procedure converges on a stop-signal delay at which participants inhibit approximately 50% of the time. This stop-signal delay represents the amount of handicapping that is necessary to tie the race. At that delay, the outcome of the race depends on random variation. Thus, it is known, on average, the point in time at which the inhibition process finishes, and that knowledge can be used to estimate stop-signal reaction time.

The estimation of stop-signal response time is illustrated in the diagram below. The race depends on three quantities: go-signal reaction time, stop-signal reaction time, and stop-signal delay. Two of these quantities (go-signal reaction time and stop-signal delay) are known. Moreover, because individuals inhibit 50% of the time at the critical delay, stop-signal reaction time plus stop-signal delay must equal the average reaction time to the go task (go-signal reaction time). Stop-signal reaction time is calculated simply by subtracting stop-signal delay from go-signal reaction time.



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