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J. Experimental Child Psychology 87 (2004) 201–220
Journal of Experimental Child Psychology
www.elsevier.com/locate/jecp

Developmental trends in simple and selective inhibition of compatible and incompatible responses

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Received 22 July 2002; revised 6 November 2003

Abstract

This study examined age-related change in the ability to inhibit responses using two varieties of the stop signal paradigm. Three age groups (29 7-year-olds, 24 10-year-olds, and 28 young adults) performed first on a visual choice reaction task in which the spatial mapping between the go signal and response was varied between blocks. The choice task was then complicated by randomly inserting a visual stop signal on 30% of the trials. In the simple stop signal paradigm, the stop signal required the inhibition of the planned response. In the selective stop signal paradigm, the stop signal required response inhibition only when the stop signal was presented at the same side as the instructed response to the go signal. The results showed that simple stopping was faster than selective stopping and that selective, but not simple, stopping of incompatible responses was slower than stopping of compatible responses. Brinley plot analysis yielded linear functions relating children's latencies to adults' latencies. Analysis of shared variance indicated that developmental change in the speed of selective stopping continued to be significant even when the effect associated with simple stopping was removed. This pattern of findings is discussed vis-à-vis notions of global versus specific developmental trends in the speed of information processing.

Keywords: Inhibition; Stop signal paradigm; Signal–response compatibility; Processing speed; Development

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doi:10.1016/j.jecp.2003.11.003

Traditionally, developmental theories have emphasized the role of changes in the capacity to store and process information in accounting for cognitive development (e.g., Case, 1985; Halford, 1993; Pascual-Leone, 1970). More recently, the concept of *inhibition* emerged from the literature (Howe & Pasnak, 1993) as a key construct in explaining cognitive development (Bjorklund & Harnishfeger, 1995; Dempster, 1993; van der Molen, 2000) and interpreting deficiencies in childhood psychopathology (e.g., Barkley, 1997; Quay, 1997). The umbrella term *inhibition* covers a variety of constructs belonging to at least two broad categories (e.g., Smith, 1992). One meaning of inhibition refers to hierarchical control of a lower force by a higher force, whereas the other notion of inhibition denotes a competitive relation between qualitatively equivalent powers in which one force leads to the temporary arrest of the other force. The former notion seems central to Dempster's (1993) theorizing that presents a synthesis between developmental research (suggesting that resistance to interference contributes to diverse expressions of cognitive development), on the one hand, and neuropsychological research, on the other, with both indicating that the frontal lobes are critically involved in interference-sensitive tasks. Dempster's *susceptibility to interference model* attributes a major role to the executive functions exercised by the prefrontal cortex and, thus, seems to emphasize active suppression as key construct. Bjorklund and Harnishfeger (1995) emphasized the latter notion and hypothesized that inhibitory processes become more efficient during childhood, resulting in less irrelevant information entering working memory and, thus, increasing its functional capacity. These authors conceptualized processing efficiency in terms of activation speed and conceptualized inhibition in terms of a process that blocks the spread of activation (see also Harnishfeger, 1995). In this regard, the *inefficient inhibition model* seems to emphasize the notion of competitive interaction rather than active suppression.

The current study is concerned with the active suppression type of inhibition that is manifested in several experimental procedures ranging from relatively simple tasks, such as the Donders C task (e.g., Becker, Isaac, & Hynd, 1987), to fairly complex tasks, such as the Wisconsin Card Sorting Task (e.g., Chelune & Baer, 1986). These procedures share the requirement that a prepotent response must be suppressed. Most procedures are limited to the extent that the processes involved in response suppression must be inferred from the absence of the prepotent response (e.g., Donders C task), from the slowing of the correct response (e.g., Wisconsin Card Sorting Task), or from noninvasive electrophysiological measurements (e.g., event-related brain potentials). One exception is the stop signal paradigm developed by Vince (1948; see also Lappin & Eriksen, 1966) and formalized by Logan and Cowan (1984). In the stop signal paradigm, participants usually perform a standard two-choice task (i.e., the go task). On some trials, a stop signal is presented infrequently and unpredictably, countermanding the planned response to the go signal. According to the underlying theory (Logan, 1994; Logan & Cowan, 1984), participants' ability to inhibit depends on the outcome of a race between two independent processes: the go process and the stop process. If the go process wins the race, the response will be executed. In contrast, if the stop process wins the race, the planned response will not occur. Thus, the ability to inhibit depends on the latency of the stopping response to the stop signal (i.e., stop signal reaction time [RT]). The clear advantage of the stop signal paradigm over other procedures is that it provides a measurement of an internal act of control even though successful inhibition produces no overt behavior. Conceptually, the type of inhibition manifested in the stop signal paradigm is one of several intentional acts of control that is required in many real-life situations (e.g., stopping for a red light) and that is exercised by a higher order executive system (e.g., Norman & Shallice, 1986).

Developmental studies using the stop signal paradigm to assess inhibitory control are relatively scarce and have yielded only limited evidence of age-related change in the speed of inhibitory processes. Some studies have observed a developmental increase in the speed of stop processes (e.g., Ridderinkhof, Band, & Logan, 1999; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). Other studies, however, have failed to demonstrate systematic age-related changes (e.g., Band, van der Molen, Overtoom, & Verbaten, 2000; Jennings, van der Molen, Pelham, Brock, & Hoza, 1997; Oosterlaan, 1996; Schachar & Logan, 1990). Monte Carlo simulations performed by Band, van der Molen, and Logan (2003) suggested that the failure to obtain a developmental trend in the ability to inhibit motor responses is most likely due to a lack of power (see also Williams et al., 1999). Indeed, those studies that did obtain an age-related increase in the ability to inhibit used larger samples or based their estimates of stopping latencies on a larger number of trials. For example, Williams and colleagues (1999) found that for both children and adults, there was a significant age-related change in stopping speed that was distinct from the age-related change in response speed, but for children this effect was stronger. This finding is inconsistent with the notion that speeded information processing is mediated by a single global mechanism (e.g., Cerella & Hale, 1994). Instead, it suggests that different mechanisms are involved in stopping and executing a response (Band et al., 2000).

The stop signal paradigm has been complicated by requiring discrimination between two or more stop signals (i.e., the planned response should be inhibited to one stop signal but not to the other) or between two or more responses (i.e., the stop signal requires the inhibition of one response but not the other). Recently, Bedard and coworkers (2002) investigated developmental change across the life span in the perceptual aspect of selective inhibitory control by adding a second tone to the basic stop signal task. Thus, participants were required to respond to an X or an O in a binary choice task. In trials where the designated stop signal tone was presented, participants were required to inhibit their planned response, but in trials with the nonselected stop tone, they were to execute the required response. The results of this study indicated that the speed of selective inhibitory control improves with age throughout childhood and slows down during older adulthood. A similar but more pronounced pattern was observed for the speed of responding on the choice reaction trials. Interestingly, Bedard and colleagues demonstrated, by submitting their data to hierarchical multiple regression analyses, that simply overall speeding or slowing of responses cannot explain the age-related changes in selective inhibitory control. This finding is important for at least two reasons. First, it provides support for the race model assuming that inhibition processes are independent of go processes (Band et al., 2003; Logan & Cowan, 1984). Second, the strong age-related trend for response execution and the less pronounced trend for response inhibition present a challenge for hypotheses suggesting that age-related changes in speeded information processing are mediated by a single global mechanism (e.g., Cerella & Hale, 1994; Kail, 1988; Salthouse, 1993). Bedard and colleagues' (2002) findings suggested the possibility that the ability to withhold a planned action is one of the earliest emerging control processes (executive functions) and is also preserved the longest.

The first aim of the current study was to examine developmental change in selective inhibitory control by manipulating the motor end of inhibitory processing. We assumed that stop processes are quite similar in nature to go processes. That is, the selective processing of go signals requires perceptual discrimination, translation into an appropriate action, and then the programming and unfolding of that action. Likewise, the selective processing of stop signals requires perceptual discrimination, translation into an appropriate action (i.e., activation or inhibition of an ongoing response), and then the programming and unfolding of that action. Studies examining the motor end of selective inhibitory control are few and restricted to adults (e.g., De Jong, Coles, & Logan, 1995; Logan, Kantowitz, & Riegler, 1986). Those studies showed that the requirement to selectively inhibit one response but not the other delayed the stopping process substantially. Moreover, the increase in stopping time was more pronounced when one response out of four had to be inhibited compared with when one response out of two had to be stopped (Logan et al., 1986). Our goal was to investigate the age-related change in selective inhibitory processing throughout childhood and contrast the developmental trend in selective stopping with age-related changes in simple stopping (i.e., withholding responses whenever a stop signal is presented). Participants were asked to respond to a left- or right-pointing arrow with a left- or right-hand button press. In stop signal trials, a visual stop signal was presented to the left or right of the central arrow. The stop signal required participants to inhibit their response to the arrow, but only when the location of the stop signal corresponded with the location of the response. We predicted a more marked slowing of selective stopping compared with simple stopping due to the added requirement to determine whether the response should be inhibited given its location vis-à-vis the location of the planned response.

The second aim of the current study was to investigate whether the speed of selective inhibition is determined by the response that has to be stopped. As indicated previously, Logan and colleagues (1986) observed that stopping one response out of four is slower than stopping one response out of two. This observation suggests the possibility that the response selection demands imposed by the go task influence the processes involved in selective inhibitory control. In the current study, we manipulated the response selection demands of the go task by varying spatial signal–response compatibility. There is a vast literature that spatial signal–response compatibility alters the speed of response selection (for a review, see Sanders, 1998). Thus, in compatible blocks of trials, participants responded to the direction indicated by the arrow stimulus, whereas in incompatible blocks of trials, a left-pointing arrow was assigned to a right-hand button press and a right-pointing arrow was assigned to a left-hand button press. The typical finding is that incompatible responses are substantially slower than compatible responses due to the need to suppress the incipient activation of the compatible response (e.g., Kornblum, Hasbroucq, & Osman, 1990). In line with the findings reported by Logan and colleagues (1986), we predicted that the selective inhibition of an incompatible response would be slower than the selective inhibition of a compatible response. In addition, we predicted that simple stopping would not be affected by signal–response compatibility (Logan, 1981; Logan & Irwin, 2000). Finally, the manipulation of spatial signal–response compatibility allowed us to examine whether the developmental trends in simple and selective stopping would be different from age-related changes in the ability to inhibit a spatially compatible response when the task requires the opposite response.

Method

Participants

The current study consisted of 81 participants from three age groups. For two of the groups, 29 7-year-olds (mean age = 7.2 years, $SD = 0.5$) and 24 10-year-olds (mean age = 10.4 years, $SD = 0.4$) were recruited from local elementary schools (Table 1). For all of these children, informed consent was obtained from parents and teachers. In addition, 28 undergraduate students of the Universiteit van Amsterdam (mean age = 21.9 years, $SD = 2.9$) participated and received course credit for participation. According to self-reports, all participants were healthy and had normal or corrected-to-normal vision. Mean percentile scores on Raven's Progressive Matrices test (Raven, 1988) did not differ significantly, suggesting that participants in different age groups were comparable in terms of intelligence (59.5, 59.4, and 65.7% in young children, older children, and young adults, respectively, $F < 1$).

Apparatus and stimuli

In all tasks, the go signal was a green arrow presented centrally against a black monitor background. This stimulus was terminated by participants' response or 1000 ms after signal onset. Interstimulus intervals varied randomly, but equiprobably, from 1250 to 1750 ms in steps of 125 ms. During the interstimulus intervals, a white fixation point (3×3 mm) was shown in the center of the screen. The target arrow pointed either left or right and was flanked on both sides by a square

Table 1
Descriptive statistics for participants

Age group	*n*	Gender (boys/girls)	Age (years)		Raven progressive matrices score	
			M	*SD*	*M*	*SD*
7-year-olds	29	13/16	7.2	0.5	59.5	23.6
10-year-olds	24	11/13	10.4	0.4	59.4	22.2
Young adults	28	7/21	21.9	2.9	65.7	22.7

(2×2 cm) that remained on the screen in the task. The total stimulus display subtended a visual angle of 9.1°. Keyboard keys "z" and "/" recorded left- and right-hand responses, respectively, from the onset of the go signal to the presentation of the next go signal.

Experimental tasks

There were three experiment tasks: the choice task, the simple stop task, and the selective stop task. Fig. 1 provides a graphical representation of the nature of the trials in these tasks.

Choice task

Participants responded to the direction of the arrow. Left and right arrow directions were varied randomly within blocks of trials. There were two types of trial blocks: compatible and incompatible. In the compatible condition, participants responded to the position indicated by the central arrow (e.g., if the arrow pointed

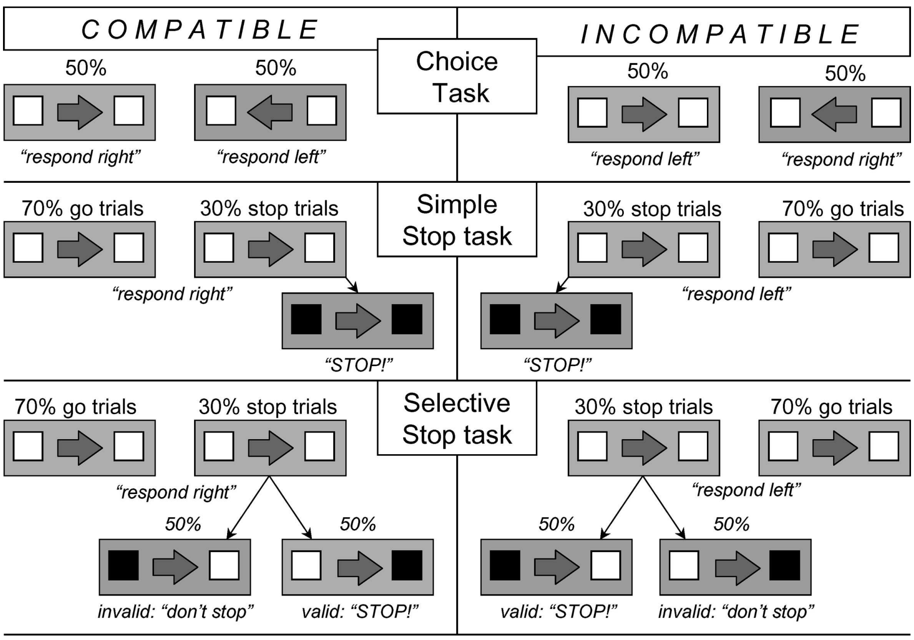

Fig. 1. Schematic of the trial structures in the choice task, the simple stop task, and the selective stop task. The go task in the simple and selective stop tasks was identical to the choice task. All tasks were administered in two compatibility conditions where the spatial mapping between the go signal and the go response was varied (compatible vs incompatible mapping). In the simple stop task, participants were instructed to stop their response to the arrow if the two squares turned red. In the selective stop task, participants inhibited their response to valid stop signals but not to invalid stop signals (see text for further details). Only trials with arrows pointing right (50% of all trials) are shown as stop task examples. Similar logic applies to arrows pointing to the left (50% of all trials).

to the left, they pressed the left button). In the incompatible condition, participants responded to the opposite position (e.g., if the arrow pointed left, they pressed the right button). Both compatible and incompatible trial blocks in the choice task consisted of 100 experimental trials.

Simple stop task

Participants performed the choice task as described previously, but on 30% of the trials a simple stop signal was presented instructing participants to refrain from responding. The simple stop signal was indicated by changing the color of the two squares on either side of the target arrow from white to red for a period of 250 ms. A tracking algorithm (Levitt, 1971) that controlled stop signal delay (i.e., the delay between the onset of the go signal and the onset of the stop signal) was used to ensure the 50% successful inhibits necessary for the estimation procedure of stop signal RT (Logan, Schachar, & Tannock, 1997). This tracking procedure compensated for individual differences in go signal RT. On successful stopping, the stop signal delay in the next stop trial was increased by 50 ms. Failures to inhibit were followed by a 50-ms decrease in stop signal delay. Based on pilot work, the initial stop signal delays in the training blocks were preset at 300 ms in the 7-year-olds, at 250 ms in the 10-year-olds, and at 150 ms in the young adults. Participants received two compatible and two incompatible trial blocks of 100 trials each.

Selective stop task

Participants performed the choice task as described previously. In this task, a selective stop signal was presented on 30% of the trials. The initial stop signal delays in the training blocks were similar to those in the simple stop task. The selective stop signal consisted of one of the two squares flashing red for 250 ms. The signal instructed participants to inhibit their response, but only if the stop signal was presented at the side of the responding hand. For example, in the compatible trial block, an arrow to the right is coupled with a right-hand response, which is to be stopped only in case of a stop signal to the right of the go stimulus. In the same way, in the incompatible trials, an arrow pointing to the right is associated with a left-hand response and should be suppressed only when the left square flashes. These stop trials are dubbed *valid stop trials*. Alternatively, arrows accompanied by stop signals presented opposite to the correct response hand required a speeded go response. These trials are dubbed *invalid stop trials*. Half of the stop signals were valid, and the other half were invalid. Three test blocks were presented for each compatibility condition, with each containing 120 experimental trials.

Procedure

All participants completed all tasks. The choice task was always presented first, with compatibility instruction order counterbalanced across participants. The order of the two subsequent stop tasks was also counterbalanced across participants. The adults performed their tasks, including a computerized version of Raven's Progressive Matrices test, within a single session of 2.5 h. To avoid potentially detrimental effects of fatigue, 7- and 10-year-olds performed the tasks in two separate sessions of 1.5 h. The adults and 10-year-olds were tested in groups ranging from three (adults) to five (children) in the university laboratory (students) or in a quiet room at school. The 7-year-olds were tested individually. Each task was introduced by presenting the pertinent stimulus displays and response assignments. Participants were instructed to respond as quickly and accurately as possible. Care was taken that all participants understood the instructions well. Each task was preceded by a practice block of 100 trials. In the stop tasks, participants received the additional instruction to maintain their focus on the go task and to avoid waiting for the stop signal to occur. Each test block was followed by performance feedback. The duration of test blocks was approximately 5 min. Between blocks, there were short intermissions, and a longer rest was given before switching between compatibility conditions and tasks.

Data analysis

The first four trials of every block of trials were viewed as warm-up trials and discarded from analysis. Individual mean RTs of correct trials were calculated after the removal of outliers from the RT distribution (i.e., RTs $> M \pm 2.5SD$) on a participant-by-participant basis. One 10-year-old was excluded from the analysis because her mean go signal RTs on the choice task, the simple stop task, and the selective stop task outranged 2.5 standard deviations from the age group's mean RT.

Stop signal RTs were estimated using the race model (Logan & Cowan, 1984; for a graphical representation of the race model, see Fig. 2). According to the independence assumption of the race model, the stop process does not affect the latency of

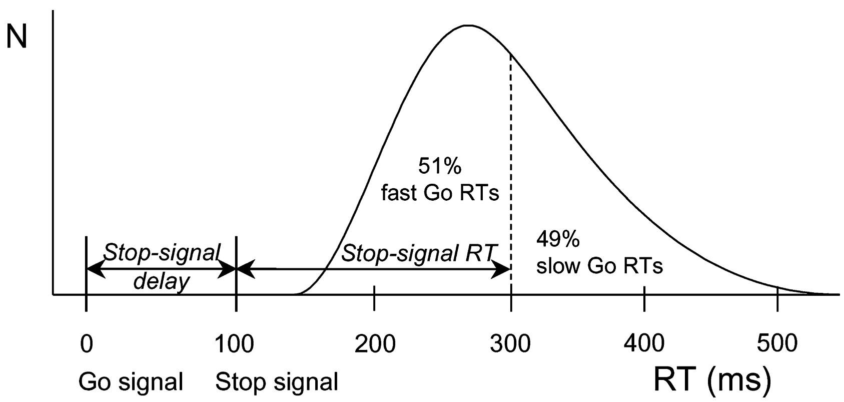

Fig. 2. Schematic representation of the race model. A distribution of reaction times (RTs) on go trials (trials without a stop signal) is shown beneath the curve. These values can be seen as finishing times of the go process. In stop trials, a stop signal was shown after the go signal at a particular stop signal delay. The finishing time of the stop process bisects the go signal RT distribution. The left part consists of go signal RTs fast enough to escape inhibition (i.e., 51%). The right part (49%) represents slow go signal RTs that will be inhibited because the stop process finished before. Stop signal RT (200 ms) is estimated by subtracting average stop signal delay (100 ms) from the RT that marks the bisection point (300 ms).

the go process. This implies that the left side of the distribution of go RTs (i.e., trials without a stop signal), representing fast responses, matches the distribution of RTs on stop trials that escape inhibition. The latency of the stop process can be estimated from the start and finish of the stop process. The start of the stop process is under experimental control by the stop signal delay, but the finish time has to be inferred from the observed go RT distribution. If responses are not stopped on n% of the stop trials, the finish of the stop process is on average equal to the nth percentile of the go RT distribution. Finally, mean stop signal delay is subtracted from this finish time to obtain an estimate of stop latency (Logan, 1994). Stop signal tracking based on inhibition rates of approximately 50% provides stop latency estimates that are derived from the center of the go RT distribution and are relatively insensitive to violations of the assumptions of the race model (e.g., Band et al., 2003; Logan et al., 1997).

Results

We begin with analyses of accuracy on the go tasks (Table 2). Analysis performed on square rooted error rates in the choice task did not reveal significant effects of age group or compatibility, nor did it reveal a significant interaction, Fs < 1. Significant age effects on choice error rates in both stop tasks, ps $< .02$, were analyzed further, showing that the youngest children made significantly more choice errors than did older participants, ps $< .02$. The error percentages of the two older age groups were comparable in magnitude, ps $> .20$. In both stop tasks, responses to go signals were less accurate when the mapping was incompatible than when the mapping was compatible, ps $< .05$. Interactions of age group and compatibility on errors on go trials were not significant, Fs < 1.

Choice task

Mean individual RTs were subjected to an analysis of variance (ANOVA) with Age Group (3) as the between-subjects factor and Compatibility (2) as the within-subjects factor. The main effects of Age Group and Compatibility were significant, $F(2,77) = 132.3$, $p < .001$, and $F(1,77) = 71.0$, $p < .001$, respectively. The analysis also yielded a significant interaction between Age Group and Compatibility, $F(2,77) = 4.4$, $p < .02$. In Table 2, it can be seen that the differences in RTs in the compatible and incompatible conditions decreased with age. Post hoc analysis indicated that the RT differences between incompatible and compatible responses were larger in 7-year-olds than in the two older age groups, $p < .01$. The two older age groups did not differ significantly in this respect, $p = .24$.

Simple stop task

Go trials

The mean go signal RTs are presented in Table 2. The ANOVA performed on these data yielded a significant main effect of Age Group, $F(2,77) = 141.4$,

Table 2
Mean go signal RT, group RT variability, standard deviation (mean), within-subject RT variability, standard deviation (within-subject), compatibility effect, and mean and standard deviation of error percentages, for compatible and incompatible signal–response mappings, in the choice task, simple stop task, and selective stop task in each age group

Task	Go signal RT							Go signal errors (percentages)			
	Compatible			Incompatible			Compatibility effect	Compatible		Incompatible	
	M	*SD (M)*	*SD (w-s)*	*M*	*SD (M)*	*SD (w-s)*		*M*	*SD*	*M*	*SD*
Choice task											
7-year-olds	559	70	116	624	103	125	65	6	5	5	4
10-year-olds	436	39	80	479	62	93	43	5	4	5	4
Young adults	326	29	41	353	37	52	27	4	4	5	4
Simple stop task											
7-year-olds	655	79	151	693	98	157	38	4	5	6	7
10-year-olds	518	78	122	523	70	111	5	2	4	3	3
Young adults	369	38	58	385	41	61	16	2	1	3	3
Selective stop task											
7-year-olds	623	74	131	650	84	141	27	3	3	5	4
10-year-olds	477	61	97	478	57	93	1	2	2	4	3
Young adults	352	33	46	368	35	53	16	2	2	3	3

Note. *SD (M)* represents averaged between-subject variability (i.e., standard deviation of mean group RT), whereas *SD (w-s)* stands for averaged within-subjects variability (i.e., standard deviation of individual trial-to-trial RT).

$p < .001$. Post hoc comparisons confirmed that the differences in go signal RT between age groups were highly significant, ps $< .001$. The main effect of Compatibility was also significant, with slower RTs for incompatible responses (534 ms) than for compatible responses (514 ms), $F(1, 77) = 15.6$, $p < .001$. The effects of Age Group and Compatibility on go signal RT interacted significantly $F(2, 77) = 3.7$, $p = .03$. Contrasts indicated that the compatibility effect was larger in the youngest age group (38 ms) than in the older age groups, $p < .01$, which did not differ in this respect, $p = .38$.

Stop trials

Table 3 presents the mean proportions of successful inhibits, stop signal delays, signal–respond RTs, and stop signal RTs for each Age Group and Compatibility combination. In all age groups, the proportions of successful inhibits were close to the anticipated 50%. The percentages of successfully inhibited stop trials did not differ between Age Groups, $F < 1$, and Compatibility conditions, $F < 1$, indicating that the tracking algorithm worked well. Mean stop signal delay decreased with age, $F(2, 77) = 74.7$, $p < .001$. The delays were longer in the incompatible mapping (275 ms) than in the compatible mapping (254 ms), $F(2, 77) = 9.1$, $p < .01$. In line with the predictions of the race model, responses on stop trials that escaped inhibition (i.e., RTs on failed inhibit trials or signal–respond RTs) were faster than go responses, $F(1, 77) = 301.8$, $p < .001$. Most important, the analysis of simple stop signal RTs yielded a significant main effect of Age Group, $F(2, 77) = 20.4$, $p < .001$. Pairwise comparisons indicated that the difference in mean stop signal RT between the youngest age group (275 ms) and the 10-year-olds (248 ms) was marginally significant, $p = .06$, whereas the 10-year-olds stopped significantly more slowly than did the young adults (207 ms), $p < .001$. The effects of Compatibility and the interaction between Age Group and Compatibility were not significant, $F < 1$ and $p = .19$, respectively. Thus, the speed of simple inhibition was about the same for compatible and incompatible responses. This was the case in all age groups, including the youngest children.

Selective stop task

Go trials

The mean go signal RTs in the selective stop task are presented in Table 2. As in the simple stop task, incompatible go responses were slower than compatible responses, $F(1, 77) = 8.7$, $p < .01$. The older age groups responded faster on go trials than did the younger children, $F(2, 77) = 171.9$, $p < .001$. The interaction between Age Group and Compatibility just failed to reach significance, $F(2, 77) = 2.3$, $p = .10$.

Invalid stop trials

Responses on trials with a stop signal appearing opposite to the correct response hand (i.e., invalid stop trials) should not be inhibited. Analyses of the percentages of response omissions in invalid stop trials resulted in a main effect of Compatibility,

Table 3
Mean inhibition ratios in stop trials, stop signal delays, signal–respond RTs, stop signal RTs, invalid stop signal RTs, omission ratios to invalid stop signals, and standard deviations for compatible and incompatible signal–response mappings, in the simple stop task and selective stop task in each age group

Stop task	Percentage successful inhibition				Stop signal delay				Signal–respond RT				Stop signal RT				Invalid stop RT				Percentage invalid stop omissions			
	Compatible		Incompatible		Compatible		Incompatible		Compatible		Incompatible		Compatible		Incompatible		Compatible		Incompatible		Compatible		Incompatible	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Simple																								
7-year-olds	49.9	3.0	50.7	3.3	357	70	400	101	569	70	602	76	282	55	267	61	—	—	—	—	—	—	—	—
10-year-olds	50.2	4.3	49.3	4.5	249	63	258	80	463	63	471	56	247	37	250	41	—	—	—	—	—	—	—	—
Young adults	49.7	3.6	50.2	4.1	156	35	166	46	343	35	360	39	205	33	209	38	—	—	—	—	—	—	—	—
Selective																								
7-year-olds	50.5	3.2	49.8	3.1	292	83	281	90	568	69	630	115	314	55	340	86	711	85	752	105	3.2	3.2	5.6	6.0
10-year-olds	43.6	7.6	41.2	9.4	187	53	178	47	469	60	470	60	292	54	309	68	542	65	541	66	3.3	2.3	4.0	3.3
Young adults	46.1	6.1	45.5	6.8	121	32	124	35	340	31	352	31	232	33	242	31	403	43	420	52	1.7	1.3	2.5	2.4

$F(1,77) = 8.4$, $p < .01$, and of Age Group, $F(2,77) = 8.0$, $p < .001$. Follow-up comparisons indicated that the 7-year-olds omitted more responses to invalid stop trials than did the two older groups, $p < .001$, which did not differ, $p = .21$. The ANOVA performed on RTs in invalid stop trials yielded a significant main effect of Age Group, $F(2,77) = 175.9$, $p < .001$, as well as of Compatibility, $F(1,77) = 6.4$, $p < .05$. The interaction between Age Group and Compatibility was marginally significant, $F(2,77) = 2.6$, $p = .08$.

Valid stop trials

The mean proportions of successful inhibits, stop signal delays, signal–respond RTs, and mean stop signal RTs in the selective stop task are presented in Table 3 for each Age Group and Compatibility combination. The tracking algorithm worked well in the selective stop task. Mean stop signal delay decreased with age, $F(2,77) = 60.5$, $p < .001$, from 287 ms in the youngest children, to 183 ms in the 10-year-olds, to 123 ms in the young adult group, pairwise comparisons ps $< .001$. In line with the predictions of the race model, responses in stop trials that escaped inhibition were faster than go responses, $F(1,77) = 31.6$, $p < .001$. The ANOVA performed on the selective stop signal RTs yielded a significant effect of Age Group, $F(2,77) = 21.4$, $p < .001$. The selective stop signal RT of 7-year-olds (327 ms) did not differ significantly from the selective stop signal RT observed in the 10-year-olds (300 ms), $p = .22$. But young adults selectively stopped their responses 63 ms faster than did 10-year-olds, $p < .001$. The main effect of Compatibility was significant; compatible responses were stopped faster than incompatible responses, $F(1,77) = 12.7$, $p < .001$. The interaction between Age Group and spatial Compatibility on selective stop signal RTs was not significant, $F < 1$.

Developmental trends in response activation and response inhibition

Two analytical techniques were applied to investigate developmental trends in performance. The first, called Brinley analysis, consists of plotting the RT data of a particular age group against those of young adults, either across levels of a task or across tasks varying in complexity (Brinley, 1965). Studies employing Brinley analysis indicate that simple mathematical equations accurately predict the response latencies of the child group obtained in a wide variety of RT tasks from the latencies of the young adults (e.g., Kail, 1988; for a review, see Cerella & Hale, 1994). These results are generally taken to support the conclusion that developmental change in the speed of responding is task independent (but see Bashore, 1994). The second procedure used to assess developmental trends in stopping involved analysis of covariance (ANCOVA). This procedure allows for an examination of the unique variance explained by a variable after accounting for the variance associated with another variable. Using analyses of shared variance, Williams and colleagues (1999) and Bedard and colleagues (2002) established distinct developmental trends in the inhibition versus execution of prepotent responses (see also Ridderinkhof et al., 1999).

Brinley plot analyses

First, mean RT data of the 7- and 10-year-olds on all tasks were plotted against the mean RT performance of the young adults for each corresponding condition (Fig. 3). For both groups of children, linear regression functions with a negative intercept and a slope greater than 1 provided an excellent fit of the data, explaining approximately 99% of the variance, $y = 2.37x - 212.6$ and $y = 1.58x - 79.7$ for the 7- and 10-year-olds, respectively. Within this context, this pattern of findings would be taken to suggest that go signal RTs, simple stop signal RTs, and selective stop signal RTs are mediated by a single mechanism.

ANCOVA analyses

Additional analysis of the data was conducted to establish whether the observed age-related change in selective stop signal RT was distinct from the age-related change in simple stop signal RT. First, ANCOVA on selective stop signal RT, entering simple stop signal RT as a covariate, showed that a significant main effect of Age Group persisted. Age explained 36% of the variance in the selective stop task and still explained a significant 13% of the variance after holding constant the age trend on simple stopping, $F(2, 75) = 6.2$, $p < .01$. Second, contrast analyses performed on corrected selective stop signal RT indicated that this effect was caused by a significant difference between the 10-year-olds and the young adults, $p = .02$. The two youngest age groups did not differ, $p = .90$.

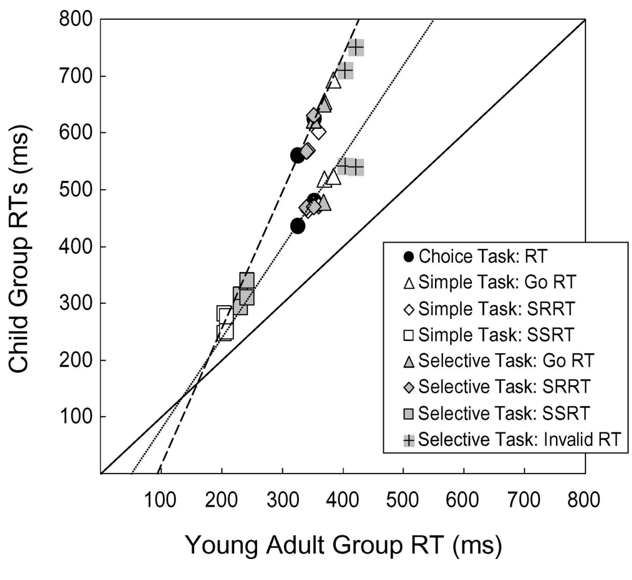

Fig. 3. Mean RTs of the 7-year-olds (dashed line) and 10-year-olds (dotted line) as a function of the mean RTs in the young adult group in the corresponding experimental condition. The dotted and dashed lines are fit to the reaction time (RT) data from the groups' compatible and incompatible choice RT task. SRRT, signal–respond RT; SSRT, stop signal RT.

Discussion

This study was conducted to examine developmental change in the ability to inhibit a prepotent response. We used the stop signal paradigm to compare age-related changes in simple and selective inhibition and assessed the influence of spatial signal–response compatibility on the speed of inhibition and response execution. First, as anticipated, compatibility had a substantial effect on response execution. The costs of responding to an incompatible stimulus were more pronounced in magnitude in the youngest children relative to the older children and young adults but were proportional in effect size. The slowing of responses in incompatible trials may be interpreted as being due to the time required to inhibit the prepotent response prior to executing the instructed, but less compatible, response (e.g., Kornblum et al., 1990). Despite disagreements about mechanisms, most investigators seem to agree that a rapid transient activation of the compatible response to a stimulus occurs (Hommel & Prinz, 1997) and that this must be inhibited when an incompatible response is required. Along these lines, the proportional slowing observed in the youngest children in incompatible trials can then be interpreted to suggest that they experience similar difficulties as do older children and adults in resolving the conflict between the transient activation of the compatible response and the execution of the instructed response.

Second, the simple stop results replicated the findings reported in previous developmental studies showing that the speed of simple inhibition improved throughout childhood (Ridderinkhof et al., 1999; Williams et al., 1999). The speed of simple inhibition increased from 275 ms in the 7-year-olds, to 248 ms in the 10-year-olds, to 207 ms in the young adults. Other studies, however, have failed to observe systematic change in the speed of simple inhibition during childhood (e.g., Band et al., 2000; Jennings et al., 1997; Oosterlaan & Sergeant, 1998; Schachar & Logan, 1990). Both Ridderinkhof and colleagues (1999) and Williams and colleagues (1999) interpreted this apparent discrepancy by referring to differences in sample size across studies. Accordingly, each of the child groups in their studies contained more than 40 children, whereas the child groups in the Band and colleagues (2000) study, for example, consisted of only 16 children. The youngest age group in the current study contained 29 children, yet the current study revealed systematic age-related changes in the ability to inhibit. The current findings, then, may suggest that stopping methodology is more important than sample size per se. Studies that have failed to observe systematic age-related change in the speed of inhibition typically used fixed stop signal delays, whereas studies that have showed a developmental increase in stopping speed used a tracking algorithm for setting stop signal delay.[1] Interestingly, the speed of

[1] One exception is the Band and colleagues (2000) study that used tracking but failed to observe systematic age-related change in stopping speed. In that study, however, the tracking algorithm was targeted at three different delays: one aiming at 30% failed inhibits, a second delay aimed at 50%, and a third aimed at 70%. The 30% and 70% tracking might have compromised the results obtained by Band and colleagues given that simulation studies have demonstrated that 50% tracking is optimal for obtaining reliable estimates of stop signal RT (Band et al., 2003).

simple inhibition of a prepotent response was not affected by the compatibility of that response with the response signal. That is, the speed of stopping a compatible response in an "all-or-none" manner does not differ from the speed of stopping an incompatible response. This finding is consistent with the results for hand responses reported by Logan (1981) and Logan and Irwin (2000). Apparently, stop signal inhibition does not interact with the suppression of a compatible response if an incompatible response has to be emitted. The current study showed that this conclusion extends to children in different age groups.

Third, the results of the selective stopping task showed that the speed of selective inhibition increased with advancing age. Selective stop signal RTs decreased from 327 ms in the 7-year-olds, to 300 ms in the 10-year-olds, to 237 ms in the young adult group. Relating these results to the findings reported previously by Bedard and colleagues (2002), it should be noted that they found a larger change in stop signal RTs between ages 7 and 9 to 12 years and found a smaller change between ages 9 to 12 and 22 years, precisely the opposite of the pattern observed in the current study. The apparent discrepancy is most likely due to a difference in design. Bedard and colleagues manipulated perceptual processes related to selective inhibition, instructing participants to decide to inhibit or execute the response based on the discrimination between two auditory stop signals. The relatively small difference in selective stopping speed that they observed between ages 9 to 12 and 22 years seems to suggest that inhibition processes drawing on perceptual processes reach mature levels during adolescence. In contrast, the experimental design employed in the current study focused on response-related processes involved in selective stopping, as participants were required to base their stopping response on the mapping between the stop stimulus and the go response. Apparently, inhibitory control drawing on response-related processes develops relatively late, that is, beyond adolescence.

Importantly, and in contrast to the simple stopping results, the selective inhibition of prepotent motor responses interacted with the spatial compatibility of the responses. All age groups selectively stopped compatible responses faster than they stopped spatially incompatible responses. The sensitivity of selective stop signal RT to the signal–response mapping of the go task extends previous findings showing an interaction between stopping and inhibitory demands of the go task (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Ridderinkhof et al., 1999). The effect of spatial compatibility on selective stop signal RT can be explained in terms of rule interference. On compatible stop trials, the go task selection rule and the inhibition task selection rule are congruent. That is, the go task stimulus is translated into the activation of a response at the side indicated by the direction of the stimulus (i.e., compatible mapping), and the stop stimulus is translated into the inhibition of a response activated at the same side as the stop stimulus (i.e., compatible mapping). In incompatible stop trials, however, the selection rules are incongruent. In those trials, the go signal is translated into the activation of a response at the side that is opposite to the location indicated by the direction of the stimulus (i.e., incompatible mapping). In contrast, as in compatible stop trials, the stop stimulus is translated into the inhibition of a response activated at the same side as the stop stimulus (i.e., compatible mapping). The interference between selection rules on incompatible trials may have caused the delay in selective stop signal RT.

Finally, stopping and response latencies were subjected to Brinley plot analyses to assess developmental trends in response inhibition and activation. The results that emerged from these analyses revealed that age-related change in response stopping and activation are well described by linear regression functions with slopes of 2.37 and 1.58 for the 7- and 10-year-olds, respectively. This pattern of findings is consistent with several previous studies using Brinley plot analysis to assess developmental trends in the speed of responding. Thus, Kail (1991) reported data from an exhaustive meta-analysis showing that children's speed of responding increased linearly as a function of adults' latencies across the 75 studies included in the meta-analysis. Similar results were obtained for a supplementary meta-analysis showing slopes of 2.37 and 1.47 for 7- and 12-year-olds, respectively, corresponding closely with the current data (Kail, 1993). Similar results were obtained from experimental work (e.g., Hale, 1990; Kail & Park, 1992; for a review, see Cerella & Hale, 1994). Thus, results emerging from Brinley plot analysis of developmental change in processing speed, including the current findings, seem to converge on the conclusion that some sort of global mechanism limits the speed with which children process information.

At this point, however, it should be noted that Brinley plot analysis of age-related change in processing speed and the global trend hypothesis that goes with it have been criticized on various counts. One issue refers to the potentially obfuscating properties of Brinley plot analysis (e.g., Perfect, 1994). That is, Brinley plot analysis might not provide a comprehensive characterization of the effects of age-related changes in information processing speed (but see Myerson, Wagstaff, & Hale, 1994). Thus, it has been noted that evidence for a global trend has typically been provided by Brinley plot analysis, whereas evidence suggesting task-dependent changes is derived from regression analysis and ANOVA (for a detailed exposition of this issue, see Bashore, 1994). Indeed, the Brinley plot analysis performed on the current data yielded evidence for a global mechanism mediating age-related changes in the speed of both response activation and response inhibition. In contrast, the results of the ANCOVA indicated that, even after removing the age-related change in simple stopping speed, the developmental trend in selective stopping speed continued to explain a significant proportion of the variance. This finding suggests distinct developmental trends in the speed of simple stopping versus selective stopping. Obviously, a resolution of the controversies surrounding the analytical procedures employed in assessing age-related changes in information processing speed is beyond the scope of the current study. At this point, it seems fair to conclude that the current results provided evidence for both a global and a specific developmental trend in the speed of information processing. A strong global trend is supported by the linear functions generated by the Brinley plot analyses and the main effect of Age Group yielded by the ANOVA. A modest, but significant, specific trend associated with selective stopping is supported by the results that emerged from the ANCOVA.

The finding of a specific developmental trend in the speed of selective stopping is important vis-à-vis the current discussion on inhibition mechanisms invoked in stopping tasks (e.g., Band & van Boxtel, 1999). Behavioral evidence suggested to Logan

(1994) that simple inhibition would be mediated by a peripheral mechanism, whereas selective inhibition requires a central mechanism. Psychophysiological findings, however, led van Boxtel, van der Molen, Jennings, and Brunia (2001) to suggest that both simple and selective inhibition invoke central processing. In contrast, the psychophysiological findings obtained previously by De Jong and colleagues (1995) suggested to them that a single peripheral mechanism mediates both simple and selective inhibition. The current data provide support for the notion, originally submitted by Logan (1994), that simple inhibition and selective inhibition are mediated, at least in part, by different mechanisms.

In closing, it is important to note that the speed of selective stopping was considerably slower than the speed of simple stopping. This finding is suggestive of the relatively high demands on cognitive control processes imposed by the selective inhibition task (cf. Bedard et al., 2002). The simple inhibition paradigm consists of just detecting the stop signal and then aborting the response to the go task. The selective inhibition task requires keeping the selection rule active in working memory (i.e., inhibit the response, but only when the stop signal is presented at the side of the instructed response), using set-shifting abilities (i.e., inhibit the response in valid stop trials and execute the response in invalid stop trials), and selecting rules (i.e., translation of the stop signal into the appropriate response: stop vs go). These cognitive control processes have been shown to develop throughout childhood (Pennington, 1994; Span, 2002) and may have contributed to the observed age-related change in selective inhibition that was more pronounced than the trend typically found for simple inhibition.

Acknowledgments

This research was supported by NWO/MaGW Grants 575-63-082C/575-25-005, the Psychology Research Institute of the Universiteit van Amsterdam, and a grant from Fondation Fyssen. We thank Bert van Beek for programming the computer tasks. We gratefully acknowledge Katja Hesse, Rolf Jansen, Chris van der Hout, Simon van der Steen, and Vanessa van Houtum for their pilot work as well as Nannie Faber, Mathilde Gouwetor, Lotte Haverman, Winnie Hendriks, Karijn van der Haar, and Marlies van Gansewinkel for their help in collecting part of the experiment data. Finally, we express our appreciation to Geert van Boxtel, Eveline Crone, and three anonymous reviewers for their valuable comments on earlier drafts of this article.

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