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van den Wildenberg, W.P.M.

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Developmental fractionation of the ability to inhibit : Differential rates of age-related change in simple and selective inhibitory control

Abstract

This study examined age-related change in the ability to inhibit using two varieties of the stop-signal paradigm. Three age groups (39 7-years olds, 24 10-year-olds, and 28 young adults) performed first on a visual choice reaction task in which the spatial mapping between stimulus and response was varied between blocks. The choice task was then extended 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 primary-task stimulus. The results showed a substantial effect of S-R compatibility on the speed of responding that decreased with age. The S-R compatibility effect disappeared when stop signals were introduced to the visual choice reaction task. Most importantly, both simple and selective stopping improved throughout childhood but at different rates. The age-related change in the speed of selective inhibition was more pronounced compared to simple inhibition. This developmental fractionation of the ability to inhibit has important implications for the understanding of cognitive control processes.

1 Introduction

Traditionally, developmental theories emphasize 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* is hiding 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 and neuropsychological research 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 hypothesize that inhibitory processes become more efficient over 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 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 present 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 Test) or from non-invasive 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, subjects usually perform a standard two-choice task but 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) the subject's 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. By 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). The clear advantage of the stop-signal paradigm over other procedures is that it provides an exact 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 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 yielded only limited evidence of age-related change in the speed of inhibitory processes. Some studies observed a developmental increase in the latency of stop processes (e.g., Williams, Ponesse, Schachar, Logan, & Tannock, 1999; Ridderinkhof, Band, & Logan, 1999). Other studies, however, 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) suggest 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. Williams et al. (1999) for example 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 can be complicated by requiring discrimination between two or more stop signals (i.e., the planned response should be inhibited to one stop signal but not the other) or between two or more responses (i.e., the stop signal requires the inhibition of one response but not the other). Most recently, Bedard and co-workers investigated developmental change across the lifespan in the perceptual aspect of selective inhibitory control by adding a second tone to the basic stop-signal task (Bedard et al., 2002). Thus, subjects were required to respond to an X or O in a binary choice task. On trials during which the designated stop-signal tone was presented they were required to inhibit their planned response but on trials with the non-selected stop-tone they should execute the required response. The results of this study indicated that the speed of selective inhibitory control gets faster with age throughout childhood and slows down in older adulthood. A similar, but more pronounced pattern was observed for the speed of responding on the choice reaction trials. Most interestingly, Bedard et al. demonstrated, by submitting their data to hierarchical multiple regression analyses, that the age-related changes in selective inhibitory control cannot be explained simply by overall speeding or slowing of responses. This finding is important first by providing support for the horse-race model assuming that inhibition processes are independent from go processes (Logan & Cowan, 1984; Band et al., 2003). Second, the strong age-related trend for response execution and the less pronounced trend for response inhibition presents 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). Their findings suggested to Bedard et al. (2002) 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 (p. 107).

In this study, we examined the developmental change in selective inhibitory control by manipulating the motor end of inhibitory processing. Subjects were asked to respond to a left- or right-pointing arrow with a left- or right-hand button press. On stop-signal trials, a visual stop signal was presented to the left or right of the central arrow. The stop signal required subjects to inhibit their response to the arrow but only when the location of the stop signal corresponded with the location of the response. Studies examining the motor end of selective inhibitory control are few and restricted to adult subjects (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 to 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 both simple stopping (i.e., withholding responses whenever a stop signal is presented) and response execution. We predicted a more marked slowing of selective stopping compared to 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.

A secondary 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 above, Logan et al. (1986) observed that selective stopping one response out of four is slower compared to the stopping of one response out of two. This observation suggests the possibility that the

response selection demands imposed by the primary task influence the processes involved in selective inhibitory control. In the current study, we manipulated the response selection demands of the primary task by varying spatial stimulus-response compatibility (SRC). There is a vast literature that spatial SRC alters the speed of response selection (for a review see Sanders, 1998). Thus, on compatible trial blocks subjects responded to the direction indicated by the arrow stimulus whereas on incompatible blocks of trials a left-pointing arrow was assigned to a right-hand button press and a right-pointing arrow 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 et al. (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 SRC (Logan, 1981; Logan & Irwin, 2000). Finally, the SRC manipulation 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.

4.2 Method

4.2.1 Participants

The present study included ninety-one participants from three age groups. A group of thirty-nine 7-year-olds (M age = 7.3, SD = 0.4), and a group of twenty-four 10-year-olds (M age = 10.4, SD = 0.4) were recruited from local elementary schools (see Table 4.1). For all children, informed consent was obtained from parents and teachers. Twenty-eight undergraduate students of the Universiteit van Amsterdam (M age = 21.9, SD = 2.9) participated and received course credits for participation. According to self-report, all subjects were healthy, and had normal or corrected-to-normal vision. They were naive about the experimental hypothesis. Mean percentile scores on the Raven Progressive Matrices (RPM) did not differ significantly, suggesting that subjects in different age groups were comparable in terms of intelligence (52%, 61%, and 66% in the young and older children and young adults respectively, F (2, 82) = 2.4, p = .10).

Table 4.1: Number of subjects, mean age in years and standard deviations (in parentheses), gender, and Raven percentile scores per age group.

Age group	n	Age	Boys /Girls	Raven percentile
7-year-olds	39	7.3 (0.4)	21 / 18	52
10-year-olds	24	10.4 (0.4)	11 / 13	61
Young adults	28	21.9 (2.9)	7 / 21	66

4.2.2 *Apparatus and signals*

In all tasks, the imperative signal was a green arrow presented centrally against a black monitor background. The imperative stimulus was response terminated or terminated after 1000 ms after signal onset. Inter-stimulus intervals varied randomly but equiprobably from 1250 to 1750 ms in steps of 125 ms. During the inter-stimulus intervals, a white fixation point (3 x 3 mm) was shown in the center of the screen. The target arrow either pointed left or right and was flanked on both sides by a square (2 x 2 cm) that remained on screen during 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 target signal until the presentation of the next target signal.

4.2.3 *Experimental tasks*

There were three experiment tasks; The choice task, the simple inhibition task, and the selective inhibition task.

Choice task

Subjects responded to the direction of the arrow. Left and right arrow direction was varied randomly within blocks of trials. There were two types of trial blocks: Compatible and incompatible. In the compatible condition, subjects responded to the position indicated by the central arrow (e.g., if the arrow pointed to the left, they pressed the left button). In the incompatible condition, subjects responded to the opposite position (if the arrow pointed left, subjects pressed the right button). Both compatible and incompatible trial blocks consisted of 100 experimental trials. The order of compatible and incompatible blocks was counterbalanced across subjects.

Simple stop task

Subjects performed the choice task as described above, but on 30% of the trials a global stop signal was presented, which instructed subjects to refrain from responding. The global 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) was used to ensure 50% successful inhibits, necessary for the estimation procedure of stop-signal reaction time (Logan, Schachar, & Tannock, 1997). This tracking procedure compensated for individual differences in reaction time to primary-task signals (i.e., go trials). Subjects received two compatible and two incompatible trial blocks of 100 trials each. The order of presentation was counterbalanced across subjects.

Selective stop task

Subjects performed the choice task as described above (see choice task). In this task, a selective stop signal was presented on 30% of the trials. The selective stop signal consisted of one

of the two squares flashing red for 250 ms. The signal instructed subjects to inhibit their response, but only when 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 only be suppressed when the left square flashes. These trials are dubbed *valid stop trials*. Alternatively, arrows accompanied by stop signals presented opposite to the correct response hand should elicit a speeded response. These trials are dubbed *invalid stop trials*. Three test blocks were presented for each compatibility condition containing 120 experimental trials each. Order was counterbalanced across subjects.

4.2.4 Procedure

The two older age groups (adults and 10-years-olds) performed all tasks. The choice task was always presented first, and the order of the two stop tasks was counterbalanced across subjects. The adults performed their tasks, including a computerized version of RPM, within a single session of 2.5 hours. The 10-year-olds performed the tasks in two separate sessions of two hours. This was done to avoid potentially detrimental effects of fatigue. The youngest children were randomly assigned to either the simple stopping or the selective stopping task, again to avoid effects of fatigue. The youngest children completed their tasks within a single two-hours session. Obviously, the procedural details made it impossible to analyze the data using a complete Age group (3) by Stopping task (2) design. However, based on pilot work, this analytical drawback was deemed less disadvantageous compared to negative effects associated with fatigue.

All subjects were tested in groups ranging from three (adults) to eight (children) in the university laboratory (students) or in a quiet room at school. Each task was introduced by presenting the pertinent stimulus displays and response assignments. Care was taken that all subjects understood the instructions well. Each task was preceded by at least one practice block of 100 trials. Subjects were instructed to respond as quickly and accurately as possible. In the stop tasks, subjects received the additional instruction to maintain their focus on the primary choice 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 five minutes. Between blocks there were short intermissions, and a longer rest was given before switching between tasks.

4.2.5 Data analysis

The first four trials of every block of trials were viewed as warm-up trials and discarded. Individual mean reaction times (RTs) of correct trials were calculated after the removal of outliers from the RT distribution (i.e., $RTs > M \pm 2.5 SD$) on a subject-by-subject basis. Subjects were excluded from the analysis if (a) their accuracy was below chance level (50%), and (b) their mean RT outranged 2.5 standard deviations from the mean age group RT. Application of these criteria resulted in the rejection of five 7-year-olds and one 10-year-old. Mean scores on the RPM of these subjects fell within a range of two *SDs* of the group averages.

Stop-signal reaction times were estimated using the horse-race model (Logan & Cowan, 1984). According to the independence assumption of the race model, the stop process does not affect the latency of 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 the 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 n -th percentile of the go RT distribution. Finally, mean stop-signal delay is subtracted from this finish time to obtain an estimate of stop latency (see Logan, 1994). Stop-signal tracking based on inhibition rates of 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 horse-race model (e.g., Band et al., 2003; Logan et al., 1997).

4.3 Results

4.3.1 Choice task

All three age groups performed the choice task and the individual mean RTs were subjected to an analysis of variance (ANOVA) with Age group (3) as between Ss and S-R Compatibility (SRC) (2) as within Ss factors. The main effects of Age group and SRC were significant, respectively $F(2, 82) = 116.2, p < .001$, and $F(1, 82) = 90.5, p < .001$. The analysis yielded also a significant interaction between Age group and SRC, $F(2, 82) = 6.5, p < .01$. In Table 4.2, it can be seen that the costs of making an incompatible response to the arrow stimulus decreased with age. Post-hoc analysis indicated that the RT differences between incompatible and compatible responses were larger in the 7-year-olds compared to the two older age groups ($p < .01$). The two older age groups did not differ significantly in this respect ($p = .20$).

A similar analysis was performed on error rates. This analysis again yielded a significant interaction between Age group and SRC, $F(2, 82) = 3.3, p < .05$. Post-hoc comparisons of error rates indicated that the differences in error rate between compatible and incompatible responses were largest in the 7-year-olds compared to the other two groups ($p < .02$) who did not differ ($p = .78$).

Recall that half of the youngest children were assigned to the simple stopping task whereas the other half was assigned to the selective stopping task. The comparison between subgroups failed to reveal a significant main effect of Subgroup on mean RT, $F(1, 29) = 2.8, p = .11$, or a significant interaction between Subgroup and SRC, $F < 1$. A similar pattern was obtained for error rates; main effect of Subgroup, $F < 1$, and interaction between Subgroup and SRC, $F(1, 29) = 4.7, p = .09$. These findings indicate that the subgroups did not differ in their performance on the choice reaction task, which served as the primary task in both the simple and selective stopping paradigms.

Table 4.2: Mean reaction times (RT in ms), mean error percentages, and standard deviations (in parentheses) by S-R mapping, compatible vs. incompatible, and mean effect size (incompatible – compatible) per age group in the choice task.

Age group	Stimulus-Response mapping				Effect size
	Compatible		Incompatible		
	RT	Error (%)	RT	Error (%)	
7-year-olds (all)	612 (117)	12 (10)	679 (121)	19 (12)	67
simple stopping	577 (116)	16 (13)	628 (131)	19 (18)	51
selective stopping	635 (119)	11 (8)	706 (110)	22 (13)	71
10-year-olds	436 (39)	5 (4)	479 (62)	5 (4)	43
Young adults	326 (29)	4 (4)	353 (37)	5 (4)	27

Note: Half of the youngest group was assigned to the simple stopping task and the other half to the selective stopping task. The results of each sub-group are presented separately (see text for further clarification).

4.3.2 Simple stop task

The data of three 7-year-olds (2 girls, 1 boy) were excluded because they failed to inhibit on more than 90% of the stop trials. Their mean scores on the Raven Progressive Matrices fell within two *SDs* of the mean score of their age group.

Go trials

The mean go-signal RTs are presented in Table 4.3. The ANOVAs performed on these data yielded only a significant main effect of Age group, $F(2, 65) = 70.9, p < .001$. The main effect of SRC failed to reach significance, $F < 1$, as did the interaction between Age group and SRC, $F(2, 65) = 1.3, p = .29$. A similar analysis performed on error rates yielded a comparable pattern; A significant main effect of Age group, $F(2, 65) = 46.9, p < .001$, that did not interact with SRC ($F < 1$) and the absence of a significant main effect of SRC ($p = .20$). Follow-up analyses of RT including Task as a separate factor (choice task alone vs. go task in simple stopping paradigm) yielded a main effect of Task, $F(1, 65) = 51.9, p < .001$. Responses were faster when participants performed the choice task alone compared to when they performed the choice task in the simple stopping paradigm. The main effects of Age group, $F(2, 65) = 88.1, p < .001$, and SRC, $F(1, 65) = 29.9, p < .001$, were included in a higher-order interaction with the effect of Task, $F(2, 65) = 3.3, p < .05$. Post-hoc analysis indicated that the insertion of stop signals tended to slow down compatible responses more than incompatible responses, $F(1, 65) = 22.4, p < .001$. This effect tended to be more pronounced in the 7-year-olds compared to the two other age groups ($p = .06$).

Table 4.3: Mean go-signal RT (Go RT in ms), mean error percentages, standard deviations (in parentheses) by S-R mapping, compatible vs. incompatible, and mean effect size (incompatible-compatible) per age group in the simple stop task.

Age group	Stimulus-Response mapping				Effect size
	Compatible		Incompatible		
	Go RT	Error (%)	Go RT	Error (%)	
7-year-olds	658 (137)	16 (10)	653 (117)	18 (15)	-.5
10-year-olds	518 (78)	2 (4)	523 (70)	3 (3)	.5
Young adults	369 (38)	2 (1)	385 (41)	3 (3)	.16

Stop trials

The mean proportions of failed inhibits, stop-signal delays, signal-respond RTs, and stop-signal RTs are presented in Table 4.4 for each Age group and SRC combination. It can be seen that the proportion of failed inhibits was close to 50% indicating that the tracking algorithm worked well. The 7-year olds failed to inhibit somewhat more frequently relative to the two older age groups (56% vs. 50%, $p < .01$). SRC did not affect the proportion of successful inhibits, $F < 1$. Mean stop-signal delay varied with age, $F(2, 65) = 20.5$, $p < .001$. The delays were longer in the youngest children relative to the other two age groups (319 vs. 254 and 161 ms, $p < .001$). In line with the predictions of the horse-race model, responses on stop trials that escaped inhibition (i.e., failed inhibits or signal-respond RTs) were faster than go responses, $F(1, 65) = 115.3$, $p < .001$. Most importantly, the analysis of simple SSRTs yielded a significant main effect of Age group, $F(2, 65) = 19.4$, $p < .001$. Follow-up analysis indicated the stop-signal RTs were longest in the 7-year-olds ($p < .001$) compared to the 10-year-olds and young adults who did not differ ($p = .09$). The effects of SRC and the interaction between Age group and SRC were not significant, $F_s < 1$. Thus, the speed of simple inhibition was about the same for compatible and incompatible responses. This holds in all age groups, including the youngest children.

Table 4.4: Mean failed inhibits (FI in %), mean stop-signal delays (SS-delay in ms), signal-respond RT (SRRT), stop-signal RT (SSRT), and standard deviations (in parentheses) by S-R mapping, compatible vs. incompatible, per age group in the simple stop task.

Age group	Stimulus-Response mapping							
	Compatible				Incompatible			
	FI	SS-delay	SRRT	SSRT	FI	SS-delay	SRRT	SSRT
7-year-olds	56	316 (138)	580 (120)	339 (131)	56	323 (135)	592 (129)	326 (125)
10-year-olds	50	249 (76)	463 (63)	247 (37)	51	258 (80)	471 (56)	250 (41)
Young adults	50	156 (42)	343 (35)	205 (33)	50	166 (46)	360 (39)	209 (38)

4.3.3 Selective stop task

Five subjects (2 boys, 3 girls) failed to inhibit their responses on more than 90% of the stop trials and were excluded from further analysis. Their mean Raven Progressive Matrices scores fell within two *SDs* of the mean score of their age group.

Go trials

The mean go-signal RTs are presented in Table 4.5. As in the simple stopping task, go RTs did not differ significantly between SRC conditions ($F < 1$). The older age groups responded faster on go trials than younger children, $F(2, 62) = 87.8, p < .001$. The interaction between Age group and SRC failed to reach significance, $F(2, 62) = 1.9, p = .16$. But more errors were committed in the condition that required incompatible responses compared to the condition requiring compatible responses, $F(1, 62) = 10.2, p < .01$, and accuracy improved with age, $F(2, 62) = 49.7, p < .001$. The interaction between these effects was not significant ($F < 1$).

Table 4.5: Mean go-signal RT (Go RT in ms), error percentages, and standard deviations (in parentheses) by S-R mapping, compatible vs. incompatible, per age group in the selective stopping task.

Age group	Stimulus-Response mapping				Effect size
	Compatible		Incompatible		
	Go RT	Error (%)	Go RT	Error (%)	
7-year-olds	648 (118)	18 (14)	637 (122)	26 (22)	-.11
10-year-olds	477 (61)	2 (2)	478 (57)	4 (3)	1
Young adults	352 (33)	2 (2)	368 (35)	3 (3)	16

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. The ANOVA yielded a significant main effect of Age group, $F(2, 62) = 42.1, p < .001$, but not of SRC ($F < 1$). A significant interaction between Age group and SRC was obtained also, $F(2, 62) = 3.6, p < .05$, indicating that the effect of compatibility in the youngest children was significantly different from the compatibility patterns observed in the older age groups ($p < .05$). More specifically, the youngest children responded about 43 ms *slower* to compatible invalid stop trials than to invalid stop trials with an incompatible S-R mapping. Compatibility effects did not discriminate between 10-year-olds and young adults ($p = .16$).

Valid stop trials

The mean proportions of failed inhibits, stop-signal delays, signal-respond RTs, and SSRTs are presented in Table 4.7 for each Age group and SRC combination. It can be seen that the tracking algorithm worked somewhat less well in the selective stopping task compared to the simple stopping task (60% vs. 52% respectively).¹ The ANOVA performed on the proportion of failed inhibits yielded a significant effect of Age group, $F(2, 62) = 17.0, p < .001$. Follow-up analysis indicated that the proportion of failed inhibits was significantly larger in the youngest children compared to the two older groups ($p < .001$) who did not differ in this respect.

Table 4.6: Mean RT (in ms), error percentages, and standard deviations (in parentheses) on invalid stop trials by S-R mapping, compatible vs. incompatible, per age group in the selective stopping task.

Age group	Stimulus-Response mapping				Effect size
	Compatible		Incompatible		
	Invalid RT	Error (%)	Invalid RT	Error (%)	
7-year-olds	687 (165)	29 (15)	644 (178)	37 (22)	-.43
10-year-olds	542 (65)	2 (3)	542 (65)	3 (4)	0
Young adults	403 (43)	1 (2)	421 (52)	2 (3)	18

Mean stop-signal delay varied with age, $F(2, 62) = 81.9, p < .001$. The delays were longer in the youngest children relative to the other two age groups (328 vs. 153 ms, $p < .001$). In line with the predictions of the horse-race model, responses on stop trials that escaped inhibition were faster than go responses, $F(1, 62) = 9.7, p < .01$.

The ANOVAs performed on the selective SSRTs yielded a significant effect of SRC, $F(1, 62) = 21.6, p < .001$, Age group, $F(2, 62) = 23.3, p < .01$, and their interaction, $F(2, 62) = 6.9, p < .01$. Young adults selectively stopped their responses about 63 ms faster than 10-year-

¹ The somewhat elevated proportion of failed inhibits observed in the youngest children is most likely due to the initial setting of stop-signal delay. This delay was 500 ms and worked well for most children. For some children, however, the 500 ms delay was a bit too long as suggested by a series of failed inhibits during the initial stage of the trial block. For those children, the tracking algorithm took longer tuning in to the optimal delay yielding 50% successful inhibits. In order to evaluate the consequences of sub-optimal tracking, the youngest group was split in two subgroups: One sub-optimal tracking group ($n = 6$) and one optimal tracking group for whom inhibition ratios did not differ significantly from the two other age groups ($n = 8$). The ANOVA performed on go RTs revealed significant differences between subgroups, $F(1, 12) = 5.4, p < .05$. Children from the optimal tracking group were on average about 123 ms slower compared to children from the sub-optimal tracking group. In addition, and most importantly, an ANOVA performed on SSRT comparing the optimal tracking group with the other two age groups still revealed a significant effect of Age group, $F(2, 56) = 15.4, p < .001$. The mean selective SSRTs were 359, 300, and 237 ms in the youngest children, the older children, and adults, respectively.

olds ($p < .02$), whereas 10-year-olds stopped about 113 ms faster compared to the youngest age group ($p < .001$). In all age groups, compatible responses were stopped faster than incompatible responses ($ps < .03$). Post-hoc comparisons indicated that the slowing of incompatible stopping was largest in the youngest children compared to the older subjects (81 ms, $p < .01$), while the magnitude of the compatibility effect did not differ between the two older age groups (respectively, 17 ms in the 10-year-olds and 11 ms in the young adults, $p = .71$).

Table 4.7: Mean proportions of failed inhibits (FI in %), mean stop-signal delays (SS-delay), signal-respond RTs (SRRT), stop-signal RTs (SSRT), and standard deviations (in parentheses) by S-R mapping, compatible vs. incompatible, per age group in the selective stopping task.

	Stimulus-Response mapping							
	Compatible				Incompatible			
Age group	FI	SS-delay	SRRT	SSRT	FI	SS-delay	SRRT	SSRT
7-year-olds	68	347 (100)	622 (159)	373 (150)	71	309 (67)	608 (174)	454 (169)
10-year-olds	56	187 (53)	469 (60)	292 (54)	59	178 (47)	470 (60)	309 (68)
Young adults	54	121 (32)	340 (31)	232 (33)	55	124 (35)	352 (31)	242 (31)

4.3.4 Shared versus unique effects of age group on stopping

An additional analysis of the data was conducted to establish whether the age-related change in the speed of simple and selective stopping was distinct from the age-related change in choice RT. First, analysis of covariance (ANCOVA) on simple SSRT, entering choice RT as a covariate, yielded a significant main effect of Age group, $F(2, 64) = 6.9$, $p < .01$, with Age group explaining 13% of the variance. A similar analysis was done on the selective SSRTs of the 10-year-olds and young adults, entering their simple SSRTs as a covariate. This analysis yielded also a significant effect of Age group, $F(1, 48) = 6.5$, $p < .01$, with Age group explaining 9% of the variance.

4.4 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 S-R compatibility on the speed of inhibition and response execution. As anticipated, S-R compatibility had a substantial effect on response execution and the costs of responding to an incompatible stimulus were considerably more pronounced in the youngest children relative to the older children and young adults. The slowing of responses on incompatible trials may be interpreted as 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 (see Hommel & Prinz, 1997) seem to agree that a rapid, transient activation of the compatible response to a stimulus occurs, which must be inhibited when an incompatible response is required. Along these lines, the disproportional slowing observed in the youngest children on incompatible trials can then be interpreted to suggest that they experience greater difficulties than older children and adults in resolving the conflict between the transient activation of the compatible response and the execution of the instructed response. This interpretation is consistent with the results of developmental studies using similar paradigms that require the need to suppress the transient activation of a prepotent response (for a review Van der Molen, 2000). Thus, young children experience greater difficulty in suppressing the tendency to respond to the stimulus source in Simon tasks (e.g., Christ, White, Mandernach, & Keys, 2001). Likewise, they are less able to inhibit word reading when color naming is required in Stroop tasks (e.g., Tipper, Bourque, Anderson, & Brehaut, 1989) or to resolve the conflict between competing responses to central target and flanking stimuli in an Eriksen flanker task (e.g., Ridderinkhof & van der Molen, 1995).

The effect of S-R compatibility on the speed of responding was annihilated when stop signals were introduced to the choice reaction task. The absence of a sizeable S-R compatibility effect is consistent with a study reported previously by Logan and Irwin (2000). In this study, participants were presented with central brackets with their angle pointing to the left vs. right (< or >) or Xs presented at the left or right of fixation. The stimuli required a spatially compatible or incompatible response by pressing a button or by moving their eyes. A stop signal was presented occasionally, instructing participants to withhold their response to the bracket or X. Peripheral stimuli yielded sizeable S-R compatibility effects on both hand and eye responses. But, similar to the current findings, S-R compatibility failed to influence the speed of responding to a central target stimulus. The current findings extend the Logan and Irwin (2000) results by indicating that the usual advantage of compatible reactions disappears when stop signals are inserted into the task. This pattern is reminiscent to the findings reported by studies in which S-R compatibility is manipulated within trial blocks (e.g., Van Duren & Sanders, 1988; for a review see Los, 1996). The disappearance of the S-R compatibility effect in mixed trial blocks can be interpreted within the Kornblum et al. (1990) dual-route account. That is, when the S-R mapping is known in advance, as in fixed trial blocks, participants can take advantage of the direct correspondence between the spatial stimulus and response codes rendering S-R translation unnecessary. When the mapping is variable, however, this fast route between corresponding stimulus and response codes must be suppressed and participants need to select between mutually exclusive S-R translation rules of approximately equal difficulty

(cf. De Jong, 1997, p. 226). Along similar lines, the current findings can be interpreted to suggest that the insertion of stop signals elicited a tonic suppression of the 'fast route' between spatially corresponding stimulus and response codes. If true, it is of great interest to note that even young children adopted this adaptive strategy, sacrificing the advantages of 'fast route' processing in order to prevent unacceptable levels of inhibition failures or erroneous reactions.

The simple stopping 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). Other studies, however, 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 et al. (1999) and Williams et al. (1999) interpreted this apparent discrepancy by referring to differences in sample size across studies. Thus, the child groups in their studies contained over 40 children each whereas in the Band et al. (2000) study, for example, the child groups consisted of only 16 children. The youngest age group in the current study contained 39 children but 20 were assigned to the simple stopping paradigm and 19 to the selective stopping paradigm. 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 failed to observe systematic change in the speed of inhibition as children grow older typically used fixed stop-signal delays whereas the studies showing a developmental increase in stopping speed used a tracking algorithm for setting stop-signal delay. One exception is the Band et al. (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 delay aimed at 70%. The 30% and 70% tracking might have compromised the results obtained by Band et al. as simulation studies demonstrated that 50% tracking is optimal for obtaining reliable estimates of SSRT (Band et al., 2003).

The speed of simple inhibition was not affected by S-R compatibility. That is, the speed of stopping a compatible response does not differ from the speed of stopping an incompatible response. Although this finding is consistent with the results for hand responses reported by Logan and Irwin (2000), it is surprising in view of findings demonstrating an interaction between stopping and compatibility in the Eriksen flanker paradigm (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Ridderinkhof et al., 1999). In the Eriksen flanker paradigm, simple SSRT is delayed when the response to the central target must compete with the opposite response elicited by the flankers surrounding the target. This finding has been taken to suggest that stopping and the need to inhibit the (incorrect) response to incompatible flankers queue up, or compete for execution (cf. Ridderinkhof et al., 1999). The current absence of an S-R compatibility effect on simple stopping does not seem to mesh with this interpretation as the need to inhibit the spatially compatible response when the instructed response is required should, likewise, interfere with simple stopping. One could argue, however, that the interaction between simple stopping and S-R compatibility did not occur because the insertion of stop signals abolished the S-R compatibility effect. This does not seem to be a compelling conjecture in view of the current selective stopping results. Choice RT in the selective stopping paradigm was not influenced by S-R compatibility, as in the simple stopping paradigm, but, unlike simple SSRT, selective SSRT revealed a substantial effect of S-R compatibility.

The results of the selective stopping task showed that the speed of selective inhibition increases throughout childhood. When interpreting their selective inhibition findings, De Jong et al. (1995) argued that participants might adopt at least two strategies to accomplish their task. One is to stop all responses and then re-activate the required response after determining that this response should not be inhibited. This strategy should result in selective SSRTs that are approximately similar to simple SSRTs and in delayed responding on invalid stop trials. The current findings seem to exclude this strategy by showing considerable longer SSRTs in the selective stop task relative to the simple stop task (317 ms vs. 263 ms, respectively). Yet responding was considerably slower on invalid stop trials as compared to go trials (540 ms vs. 493 ms, respectively). This slowing could be due, however, to a Simon effect (e.g., Simon, 1990). That is, the location of the stop-signals on invalid trials might have elicited a tendency toward this location interfering with the activation of the response at the opposite location.

The other strategy suggested by De Jong et al. (1995) consists of postponing inhibitory processing until it is determined whether response inhibition is actually required and, if so, inhibition can be accomplished by simple stopping. This strategy should result in prolonged SSRTs but, as the inhibitory response would be contingent upon the outcome of a subset of component processes included in choice RT, selective SSRT is likely to be positively correlated with choice RT. Although it is difficult to exclude this possibility completely, it should be noted that choice RT in the selective stopping paradigm did not vary with S-R compatibility and yet, the selective stopping of incompatible responses was considerably slower than the inhibition of compatible responses. Based on the second strategy suggested by De Jong et al. (1995), one should be led to predict that, as choice RT did not discriminate between compatible and incompatible responses, selective SSRT should reveal a similar pattern. But it did not. All in all, the current pattern of findings suggests that the selective SSRTs reflect the operation of selective inhibition rather than an alternative strategy invoking simple inhibition.

The sensitivity of selective SSRTs to the S-R mapping in the choice RT extends previous findings showing an interaction between stopping and inhibitory demands of the primary task (Kramer et al., 1994; Ridderinkhof et al., 1999). But those studies were concerned only with simple inhibition and manipulated inhibitory demands of the primary task using an Eriksen flanker paradigm. In an Eriksen flanker paradigm, congruent trials (i.e., trials with the central target flanked by itself) and incongruent trials (i.e., trials with the central target flanked by stimuli assigned to the opposite response) are presented within mixed trial blocks. Thus the need to inhibit the competing response on incongruent trials may interfere with the need to inhibit the instructed response. In the current study, the insertion of a stop signal abolished the effect of S-R compatibility on choice RT and it was assumed that S-R translation was similar on compatible and incompatible trials. This may explain why S-R compatibility failed to influence the speed of simple SSRT. The effect of S-R compatibility on selective SSRT can be explained in terms of rule interference. On compatible stop trials, the primary task selection rule and the inhibition task selection rule are congruent. That is, the primary task stimulus is translated into the activation of a response at the side indicated by the direction of the stimulus (compatible mapping) and the stop stimulus is translated into the inhibition of a response activated at the same side as the stop stimulus (compatible mapping). On incompatible stop trials, however, the selection rules are incongruent. On those trials, the primary task stimulus is translated into the activation of a response at the side that is opposite to the location indicated by the direction of the stimulus (incompatible mapping). In contrast, as on compatible stop trials, the stop stimulus is translated into the inhibition of a response

activated at the same side as the stop stimulus (compatible mapping). The interference between selection rules on incompatible trials may have caused the delay in selective SSRTs.

At this point, one could argue that the current interpretation in terms of rule interference is incompatible with the horse-race model assumption of independence. The rule-interference interpretation is likely to assume an interaction between primary-task processes and selective stop processes and such an interaction may render SSRT estimates based on the horse-race model unreliable. It should be noted, however, that the rule-interference interpretation refers to *functional* dependence and does not imply *stochastic* dependence. The former relates to a single factor influencing choice RT and SSRT whereas the latter refers to trial-by-trial variability in SSRT than can be predicted on the basis of trial-by-trial variability in choice RT. The horse-race model assumes only stochastic independence (e.g., Logan & Cowan, 1984; see also Ridderinkhof et al., 1999 for a similar reasoning). Moreover, simulation studies revealed that reliable estimates of SSRT can still be obtained even when the data violate the independence assumption underlying the horse-race model, in particular when the data have been obtained using the tracking of stop-signal delay targeted at 50% inhibits (Band et al., 2003).

Finally, the current findings extend previous results obtained in developmental studies using the stop-signal paradigm by allowing a direct comparison between simple and selective inhibition, although it should be acknowledged that the within-subjects comparison is based on only two age groups. Both simple and selective inhibition improved throughout childhood. The speed of simple inhibition increased from 333 ms in the 7-year-olds, via 249 ms in the 10-year-olds, to 207 ms in young adults. The corresponding selective SSRTs were 414 ms, 301 ms, and 237 ms, respectively. Although it is difficult to compare between studies, the current selective SSRT results are comparable to the findings reported previously by Bedard et al. (2002). They observed a somewhat stronger increase in the speed of selective inhibition (i.e., 456 ms, 336 ms, and 248 ms for corresponding age groups) but it should be recalled that their selective inhibition was different from ours. In their paradigm, participants had to decide between two auditory stop signals whether they had to inhibit or to execute the response as planned. In the current paradigm, participants were required to base their inhibition decision on the particular response activated by the primary-task stimulus. The Bedard et al. task focused on the perceptual end of inhibitory processing whereas the focus of the current task was on the motor end.

The developmental change in simple inhibition differed markedly from the age-related change in response execution. This finding is consistent with previous studies showing diversity in developmental trends (Band et al., 2000; Ridderinkhof et al., 1999; Williams et al., 1999). These findings argue against the hypothesis of a single, global mechanism mediating developmental change in speeded information processing (e.g., Cerella & Hale, 1994; Kail, 1988). The current selective inhibition findings are adding to the notion of differential development by showing that the age-related changes in simple and selective SSRTs cannot be reduced to a single mechanism either. This finding is preliminary as only two age groups could be included in the statistical comparison but it 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 while selective inhibition requires a central mechanism. Psychophysiological findings, however, led Van Boxtel and co-workers to suggest that both simple and selective inhibition invoke central processing (Van Boxtel, van der Molen, Jennings, &

Brunia, 2001). In contrast, the psychophysiological findings obtained previously by De Jong et al. (1995) suggested to them that both simple and selective inhibition is mediated by a single, peripheral mechanism. The current diversity in the development of simple vs. selective inhibition provides support for the notion, originally submitted by Logan (1994), that simple and selective inhibition are mediated by different mechanisms. A definitive demonstration cannot be provided by the current data but indicates an avenue for further investigation.

The diversity in developmental inhibition trends 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 simply detecting the stop signal and then abort the response to the primary task stimulus. 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), set-shifting abilities (i.e., inhibit the response on valid stop trials and execute the response on invalid stop trials), and rule selection (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 that is typically found for simple inhibition. The differential rates of developmental change in simple and selective stopping (or *developmental fractionation*) may provide a handle for future studies aimed at providing a deeper understanding of the cognitive control processes involved in the relatively simple act of stopping a motor response.

