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Acta Psychologica 101 (1999) 315–337

acta
psychologica

A study of adaptive behavior: effects of age and irrelevant information on the ability to inhibit one's actions

K. Richard Ridderinkhof [a,b,*], Guido P.H. Band [b], Gordon D. Logan [c]

[a] *Department of Developmental Psychology, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands*
[b] *Department of Psychonomics, University of Amsterdam, Amsterdam, The Netherlands*
[c] *Department of Psychology, University of Illinois at Champaign-Urbana, Illinois, USA*

Abstract

In the study of adaptive behavior, the stop-signal paradigm provides a measure of the efficiency of response suppression that lends itself to examining the ability to inhibit one's actions, and two complementary types of factors that may influence that ability. Based on neurobiological considerations, age-related individual differences were hypothesized to be such a factor. In agreement with the the cognitive-neuroscience literature, which emphasizes the relatively late maturation and early senescence of the (pre)frontal brain structures that are crucial for inhibitory control, results are reported of a study demonstrating that response inhibition in the stop task is subject to an unequivocal age trend during child development.

Stop task performance was hypothesized to be influenced further by the effects of irrelevant information. In a concurrent reaction time task, distractor stimuli may induce activation of an incorrect response. The subsequent inhibition of this incorrect response activation may interact with the suppression of responses in the stop task, if both are engaged simultaneously. Indeed, in a study designed to examine this prediction, the operation of response inhibition in the primary-task and stop processes affected one another negatively when distractors were associated with the incorrect response. © 1999 Elsevier Science B.V. All rights reserved.

PsycINFO classification: 2260; 2330; 2340; 2820

Keywords: Adaptive behavior; Response inhibition; Stop-signal reaction time; Choice reaction time; Age-related changes; Stimulus-response correspondence effects

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[*] Corresponding author. E-mail: op_Ridderinkhof@macmail.psy.uva.nl

PII: S0001-6918(99)00010-4

1. Introduction

Continuously changing events in an individual's environment place rapidly alternating demands on the individual's adaptive behavior. The capability to adjust one's actions dynamically by generating appropriate responses while at the same time maintaining coherent, goal-directed behavior, includes the capacity to stop, that is, to refrain from executing an intended or programmed action when some last-moment information calls for it. A popular illustration of this form of inhibitory control is that of the baseball hitter. In response to the pitcher's action, the hitter programs the parameters of a mighty swing, and enters the initial stages of executing the movement. However, when at the last moment the ball curves away from the plate, in a split-second the hitter decides to check his swing.

An experimental task that has been developed to examine these inhibitory aspects of adaptive behavior under controlled circumstances in the laboratory is the stop task (Lappin & Eriksen, 1966; Logan, 1994; Logan & Cowan, 1984). In this computer task, subjects are presented with stimuli whose identity designates a speeded response with one of two effectors, as in a regular binary choice reaction task. However, on occasion, the stimulus is followed (at some variable interval) by a second stimulus, the stop-signal. The stop-signal is a control signal that makes the response inappropriate, and calls for adaptive behavior in the form of inhibitory control: It tells the subject to withhold that response. As will be described in some detail below, the stop-signal paradigm provides a measure of the efficiency of response suppression that lends itself to examining the ability to inhibit one's actions, and the factors that influence that ability. The methods and tools of the stop task have become popular over the last decade, particularly in clinical settings where the task is used to study inhibitory control in pathological groups suspect of inhibitory dysfunction or deficiencies in impulse-control (see, e.g. Daugherty, Quay & Ramos, 1993; Jennings, van der Molen, Pelham, Brock & Hoza, 1997; Oosterlaan & Sergeant, 1996; Schachar & Logan, 1990).

The primary aim of the present study is to identify factors that influence the ability to suppress one's actions in a stop task. We concentrate on two candidate factors: the effects of irrelevant information, and the effects of age. Disparate as these factors may seem to be, they share a fascinating property: they are among the few factors that can be argued to have the potential to influence the ability to stop, yet have rarely been observed to do so. In addition, these influences both are argued to involve mechanisms in which response inhibition plays a key role. We set out to clarify whether and how these factors influence the inhibition of actions in a stop task; such clarification can contribute new insights to theories of response inhibition and its role in adaptive behavior. Before reporting the present experiments and rationale, we will first discuss the stop-signal task and methodology in detail.

1.1. The stop-signal paradigm

In the stop task, choice reaction time (CRT) is recorded while subjects respond to the identity of a stimulus. On occasion, after some variable interval (the stop-signal delay) this stimulus is followed by a second stimulus, the stop-signal. On the occurrence of a stop-signal, the response to the first stimulus is countermanded. At sufficiently short stop-signal delays, the stop-signal arrives in time to prevent execution of the response; at sufficiently long delays, the stop-signal arrives too late to prevent the action from being executed, and the action can no longer be stopped. The probability of response inhibition can be determined as a function of stop-signal delay by recording, on each stop-signal trial, whether the action can or cannot be stopped.

To provide a formal basis for interpreting the findings obtained in a stop task, Logan and Cowan (1984) and Logan, Cowan and Davis (1984) proposed a horse-race model that involves a race between two sets of stochastically independent processes (see also Ollman, 1973; Osman, Kornblum & Meyer, 1986). One set of processes is concerned with the selection and execution of a motor action in response to a stimulus (primary-task processes), and the other set of processes is concerned with inhibiting all motor actions in response to a stop-signal (stop processes). Whether or not the motor action is executed depends on which of the set of processes is completed first and wins the race (cf. Lappin & Eriksen, 1966; Logan & Cowan, 1984; Osman et al., 1986; see also Vince, 1948).

Crucial to the outcome of the horse race is the speed of each set of processes. In contrast to the speed of the overt primary-task response (as expressed in CRT), the speed of the internal response to the stop-signal cannot be observed directly. However, as demonstrated by Logan and Cowan (1984), an estimate of the finishing time (and hence speed) of the stop processes can be derived mathematically on the basis of three factors: stop-signal delay; the probability of responding on stop-signal trials, or *P*(response | stop-signal); and the CRT distribution of primary-task responses on no-signal trials. The procedure to calculate the speed of stopping will be described in some detail, since this index of inhibitory control is of major interest to our present purposes.

The finishing time of the stop processes can be envisioned to fall on some point in the CRT distribution: primary-task responses faster than this finishing time escape the stop-signal and cannot be inhibited; responses slower than this finishing time are too late to escape the stop-signal and are inhibited. If *P*(response | stop-signal) were observed to be 0.50, then half of the primary-task responses on stop trials would escape the stop-signal and half of the responses would be stopped. Thus, the finishing time of the stop processes would equal the time associated with the 50th percentile of the CRT distribution of primary-task responses on stop-signal trials. Similarly, if *P*(response | stop-signal) were observed to be 0.49, the finishing time of the stop processes would equal the 49th percentile of the CRT distribution, and so on. Since CRTs (and hence the finishing time of the stop processes) are determined relative to the onset of the primary-task stimulus, the duration of the stop processes (stop-signal reaction time or SSRT) is then derived simply by subtracting stop-signal delay from the finishing time of the stop processes.[1]

In a series of extensive simulation studies, aimed to evaluate the reliability and boundary conditions of the measures of response inhibition in the stop-signal paradigm, Band (1997) indicated that SSRT can be estimated most reliably when $P(\text{response} \mid \text{stop-signal})$ is close to 0.50. At this probability, the estimated value of SSRT is relatively insensitive to variability in actual SSRT or CRT, and to incomplete stochastic independence between primary-task and stop processes. To ensure that $P(\text{response} \mid \text{stop-signal})$ is close to 0.50, stop-signal delays should be calibrated individually to a subject's speed of responding and speed of stopping. Because these speeds can change during performance of the stop task, stop-signal delay should vary dynamically, contingent on the subject's behavior. A procedure that has been used extensively in psychophysics (e.g., Levitt, 1970) and is well suited for our present purpose is the staircase tracking algorithm. Stop-signal delay is changed after every stop-signal trial, increasing by 50 ms if the response is inhibited and decreasing by 50 ms when it is not. This procedure converges on a stop-signal delay at which the probability of stopping is 50% (cf. Logan, Schachar & Tannock, in press; Osman et al., 1986). In order to prevent subjects from applying a strategy of "waiting for a possible stop-signal", by which they could try to trade speed of responding for accuracy of inhibition, instructions should emphasize that speed is rewarded, and that the probability of stopping will approximate 50%, regardless of "waiting" strategies.

1.2. Sources of variability in the ability to stop

Two types of factors that affect inhibitory control may be examined to derive complementary insights in the efficiency of the processes involved in stopping one's actions. One such type of factors pertains to manipulations of the demands on inhibitory control in the primary task. Another type of factors consists of individual differences in inhibitory control. Both types of factors will be discussed in some detail to examine the potential sources of variability in the ability to stop.

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[1] Two factors complicate this procedure to calculate SSRT. First, SSRT (like CRT) is likely to display trial-by-trial variability rather than be constant. However, as argued by Logan and Cowan (1994), this feature is of negligible consequence to the accuracy of the estimate (for a detailed analysis see Band, 1997, and de Jong, Coles, Logan, and Gratton, 1990). Estimating the finishing time of the stop process is facilitated substantially if SSRT can be assumed to be a constant rather than a random variable. Second, to determine the finishing time of the stop processes as the time associated with the xth percentile of the CRT distribution, the full CRT distribution must be known. However, *de facto*, the CRT distribution on stop-signal trials can be observed only in part: the part where CRTs were fast enough to escape from the inhibition induced by the stop-signal. However, the hypothetical CRT distribution on stop-signal trials can be derived from the CRT distribution as observed on no-signal trials, because the characteristics of the distribution of CRTs to the primary task stimulus should not be influenced by the presentation and processing of a stop-signal (on the horce-race model assumption that the choice reaction processes triggered by the primary task stimulus are stochastically independent of the response-inhibition processes triggered by the stop-signal).

An important source of individual differences in response inhibition is age, through its effects on the brain mechanisms underlying inhibitory control. A rapidly growing literature documents the involvement of frontal-lobe structures, and in particular the prefrontal cortex, in inhibitory control (for reviews and discussions see, e.g. Band & van Boxtel, 1999; Clark, 1996; Knight, Staines, Swick & Chao, 1999; Pennington, 1994; West, 1996). In an elaborate survey of the literature, van der Molen and Ridderinkhof (1998) reviewed a variety of findings emerging from the neurosciences yielding strong support for the popular impression that the frontal lobes, and the control functions they subserve, display a pattern of ontogenetic maturation and senescence that is markedly different from the developmental trajectories followed by other brain areas (Bashore, 1993; Dempster, 1993; Diamond, 1990; Stuss, 1992; West, 1996). Although recognized for quite some time (e.g. Luria, 1966), the special role of frontal structures and functions in normal development and aging receives renewed interest in the light of the progress made recently in the cognitive neurosciences through the use of electrophysiological and brain-imaging techniques (see van der Molen & Ridderinkhof, 1998, for a review). The picture painted by studies examining brain growth in healthy children strongly suggests that brain growth follows a hierarchical course with frontal lobes maturing latest. Analogously, the observations reported in imaging studies of the aging brain in healthy older subjects converge on the conclusion that the frontal lobes are the first to deteriorate.

The relatively late functional maturation and relatively early deterioration of the frontal lobes suggest that the cognitive control processes, that require mature and intact frontal brain structures and connectivity, are the latest to develop and the first to decline. This "last-in, first-out" notion is consistent with recent neuropsychological models of cognitive development (e.g. Stuss, 1992), that suggest separate lower-order mechanisms for overlearned and routinized processing and higher-order mechanisms for executive control which develop at different rates. Age-related change in inhibitory control over interference from irrelevant information, irrelevant strategies, or irrelevant responses has been invoked to explain age-related change in performance on a wide variety of cognitive tasks (e.g. Bjorklund & Harnishfeger, 1990; Dempster, 1992, 1993; Dustman, Emmerson & Shearer, 1996; Hasher & Zacks, 1988; Kramer, Humphrey, Larish, Logan & Strayer, 1994; Ridderinkhof & van der Molen, 1995, 1997; Shimamura, 1995). Indeed, many researchers have amassed evidence in support of the hypothesis that inhibitory control, in contrast to some basic cognitive functions, is compromised in children and older adults (see reviews in van der Molen & Ridderinkhof, 1998; West, 1996).

Few researchers have attempted to delineate age-related changes in the speed of stopping at either end of the life span. In a study of inhibitory processing in older adults, Kramer and colleagues observed significant differences in stop task performance between young and older adults (Kramer et al., 1994). Quite surprisingly, however, in developmental studies significant age changes in SSRT have not been reported. We will discuss potential reasons for these failures, and report clear-cut results of a study demonstrating that response inhibition in the stop task is subject to an unequivocal age trend during child development.

To the extent that inhibitory control fluctuates as a function of age, we anticipate that the adaptive behavior required to perform accurately in a stop task also changes with age. This presumption suggests other potential sources of variability in adaptive behavior in a stop task: if stop task performance covaries with individual differences in inhibitory control, then stop task performance may covary also with other variations in inhibitory control. For instance, the ability to inhibit an action in response to a stop-signal may vary as a function of the demands on inhibitory control exerted by the primary task. If not only the stop processes, but also the primary-task processes involve the suppression of responses, these inhibitory processes may potentially interact with one another.

Note that this type of interaction between primary-task and stop processes (referred to as *functional dependence*), in which mean CRT and mean SSRT are influenced by a single factor, does not imply *stochastic dependence*, in which trial-by-trial variability in SSRT can be predicted accurately from trial-by-trial variability in CRT. [2] Functional dependence may well coincide with stochastic independence. The race model assumes only stochastic independence between primary-task processes and stop processes (Logan & Cowan, 1984; Logan et al., 1984; Ollman, 1973; Osman et al., 1986). Thus, it should be articulated that observations of functional dependence do not in and of themselves call into question the validity of the race-model assumptions or the reliability of SSRT (which is calculated on the basis of these assumptions).

SSRT has been reported frequently to be insensitive to the effects of experimental manipulations that vary the processing demands for the primary task (indicating functional independence; for a review see Logan, 1994), with one notable exception. This isolated finding was reported by, again, Kramer et al. (1994), who observed that the identity of distractor stimuli affected SSRT. We will discuss potential reasons for this observation, and report the results of a study confirming the hypothesis that response inhibition in the stop task interacts with the suppression of responses activated by irrelevant information. Several possible mechanisms that may produce these interactions will be evaluated.

The present experimental study consists of one experiment in two parts. The first part was administered to children in two age groups and young adults, and addresses variability in the efficiency of the processes involved in stopping one's actions as a function of age-related individual differences. The second part was administered to the adult subjects only, and addresses variations in the efficiency of the processes involved in stopping one's actions as a function of manipulations of the demands on inhibitory control in the primary task. For reasons of conceptual clarity, we will discuss the two complementary parts separately.

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[2] Formally, process M and process N are *stochastically* independent if $p(M \text{ and } N) = p(M)p(N)$, that is, if the joint probability is the product of the separate probabilities. Processes M and N are *functionally* independent if a factor affects $p(M)$ without affecting $p(N)$ or if it affects $p(N)$ without affecting $p(M)$. Functional dependence between processes M and N does not imply stochastic dependence as long as the joint probability equals the product of the separate probabilities.

2. Age changes in SSRT

Under the assumption that response inhibition can be measured adequately using SSRT in a stop task, one would expect age-related differences in normal frontal function to be expressed loud and clear in SSRT. Whereas the stop task has been used repeatedly in studies examining inhibitory control in childhood psychopathology (for a recent review see Oosterlaan, 1996), only few studies have adopted the stop task to chart the speed of stopping during normal development and senescence. The results are, at best, ambiguous. In an initial study, Schachar and Logan (1990) reported slower SSRTs for ADHD children compared to a matched control group. When the authors examined age trends in their normal controls, SSRT appeared to be subject to an age-related decrease, but statistically significant age differences were absent. A study by Band (1997) also failed to reveal significant age changes in children's SSRTs. In a group of normal children aged 8–12, Oosterlaan (1996) observed only a weak and nonsignificant negative correlation between age and SSRT. In contrast to these developmental studies, Kramer et al. (1994) in an aging study observed clear-cut differences in SSRT between age groups: SSRTs averaged 214 ms in young adults versus 305 ms in 60- to 74-year-olds.

If the speed of stopping is not subject to age-related improvement in children, then developmental theories of inhibitory control may be in need of revision. However, the experimental results cited above were not unequivocal. In the study by Schachar and Logan (1990), SSRTs averaged 326, 276, and 253 ms in, respectively, 8-, 10-, and 12-year-olds. SSRTs for adults averaged 264 ms. The apparent age trend failed to reach statistical significance, however. A decrease of comparable proportion in average SSRTs between 5-year-olds and adults was reported by Band (1997); this trend also barely failed to reach significance. Thus, it may be premature to conclude that these results indicate that maturational changes in inhibitory processes are not expressed in SSRT, or that inhibitory processes are characterized by maturational stability.

Inspection of between-subjects variance in SSRT (as expressed in ANOVA error terms) and of numbers of subjects per age group in each of these studies suggests that the ambiguous patterns of findings result, at least in part, from insufficient statistical power. Standard deviations typically amounted 20–30% of SSRT, suggesting substantial interindividual variability in the speed of stop processes, especially in children and older adults. Thus, unless large numbers of subjects provide sufficient degrees of freedom to obtain statistical support for the observed age trends in SSRT, failure to establish such trends statistically may be due to lack of power. In the study by Schachar and Logan, there were 12 subjects per age group; in the study by Band, there were 16 children per group, and 21 adults. The study by Oosterlaan included 21 children in total. The study by Kramer et al., that did report significant age differences in SSRT, included larger numbers of subjects: 32 young and 30 older adults. Thus, lack of statistical power may have been a major factor in preventing age trends in SSRT to be manifest in the developmental studies. To settle the issue of whether or not SSRT decreases as children grow older, in part I of the present study we administered a stop task to large groups of children and adults.

2.1. Method

Subjects. Children in two age groups were recruited from a local elementary school, and received a small gift after their participation. One group included 6–8-year-old children (7.8 years on average; $n = 53$); the other group included 10–12-year-olds (11.0 years on average; $n = 48$). A third group consisted of Psychology students of the University of Amsterdam (21.7 years on average; $n = 47$), who received course credits for their participation. All subjects had normal or corrected-to-normal vision.

Apparatus, stimuli, tasks, and procedure. Subjects were tested individually, but simultaneously in groups of five or six. Children were tested in a quiet and dimly lit room in their school; adults were tested in a dimly lit, sound-attentuated room in a university laboratory. They were seated 50 cm in front of a Macintosh Plus computer, that was used to control stimulus presentation and response registration. A rectangular contour presented at the centre of the computer screen (subtending visual angles of 6.27° and 1.60° of arc in the horizontal and vertical planes, respectively) served as a fixation stimulus and remained visible throughout a block of trials. The subjects' primary task was to press a button in response to the direction of an arrow (1.03° of arc horizontally and vertically) presented centrally inside the fixation contour. They were instructed to press the left key (the *z* key on the keyboard) if the arrow pointed to the left, and the right key (the "/" key on the keyboard) if the arrow pointed to the right. The arrow was presented for 500 ms, and required a response within 1500 ms after its onset. The stimulus for the next trial was presented 1500 ms after the subject's response.

On a randomly selected 25% of the trials, an auditory stimulus (1000 Hz, 70 dB, 50 ms) was presented in addition to the visual primary-task stimulus. Presentation of this tone designated that the subject was to refrain from responding to the primary-task stimulus on that trial. The time interval between the primary-task stimulus and this stop-signal was initially set to 500 ms, but subsequently this interval varied dynamically according to the staircase tracking algorithm described above, in order to converge on a stop-signal delay at which the probability of stopping is 50%. This method has been used successfully in previous studies to avoid that subjects delay their response to the primary-task stimulus to increase the probability of stopping (cf. de Jong, Coles, Logan & Gratton, 1990; Logan et al., in press; Osman et al., 1986). Stop-signal delay was changed after every stop-signal trial, increasing by 50 ms if the response was withheld and decreasing by 50 ms when it was not.

After every trial, visual feedback was presented centrally in the form of a digit that indicated the number of points earned on that trial. The feedback regime was designed to reward fast and accurate responses to the primary-task stimulus, and to discourage a strategy in which subjects awaited the occurrence of a stop-signal before responding to the primary-task stimulus. Correct responses on no-signal trials were rewarded with 2–5 points, depending on CRT on that trial relative to the subject's average CRT. Thus, the faster the response, the more points could be earned. When subjects responded with the incorrect hand, they still received one point, but failure to respond on a no-signal trial (omission error) yielded zero points. On stop-signal trials, subjects received five points upon successful response inhibition, or one point when they failed to inhibit the response (commission error).

Each subject completed four blocks of trials. The first two blocks were practice blocks, consisting of 40 trials each. Subjects were trained to prepare a response to the primary-task stimulus as if no stop-signal could occur, and to respond as quickly as possible while at the same time keeping errors to a range of 5–15%. They were instructed that on some occasions a tone would occur, and that they should try to withhold their response in that event. It was explained to them that the computer was programmed such that they would often not be able to suppress the response, and that this was no problem, as long as they just tried their best. Care was taken to ensure that these instructions were well understood. After a break, two blocks of 98 trials each were administered; the first two trials in each block were used as warm-ups and were excluded from data analysis. The blocks of trials were separated by a rest period of a few minutes. This procedure resulted in a total of 48 stop-signal trials in the experimental blocks. As shown by Band (1997), the number of stop-signal trials should be at least in the order of 40 in order to reduce the confidence interval for SSRT to an acceptable size, whereas increasing the number of stop-signal trials beyond 50 does not result in substantial reductions of the confidence interval.

In the group of 6–8-year-old, three children performed with accuracy below 60% on no-signal trials in the primary task, such that their performance did not exceed chance level; three other children failed to inhibit their responses in more than 90% of the stop-signal trials. The data from these children were not analyzed further (however, we verified that excluding these subjects did not affect the pattern of results for any of the dependent variables).

2.2. Results and discussion

On approximately 50% of the stop-signal trials, subjects were successful in inhibiting their response to the primary-task stimulus ($P(\text{response} \mid \text{stop-signal}) = 47.8$, 47.9, and 46.8% in 6–8-year-olds, 10–12-year-olds, and adults, respectively). Thus, the staircase tracking algorithm produced the expected probability of responding in stop-signal trials.

Mean CRTs for correct responses on no-signal trials, error percentages for responses on no-signal trials, and SSRTs (calculated as described above) were submitted to an analysis of variance with Age Group as a between-subjects factor. Fig. 1 shows that, as expected, CRT decreased as a function of age (685, 537, and 440 ms for 6–8-year-olds, 10–12-year-olds, and adults, respectively; $F(2,139) = 44.68$, $p < 0.001$). Accuracy increased with age (86.8, 93.5 and 96.1% for 6–8-year-olds, 10–12-year-olds, and adults, respectively; $F(2,139) = 18.97$, $p < 0.001$), suggesting that the CRT results could not be explained by age-related shifts in speed-accuracy balance alone.

Most important, SSRT was observed to decrease substantially with age: 305, 234, and 188 ms for 6–8-year-olds, 10–12-year-olds, and adults, respectively (see Fig. 1; $F(2,139) = 18.62$, $p < 0.001$). In fact, the relative magnitude of the age-related decrease in SSRT was quite similar (slightly larger in fact) to the corresponding

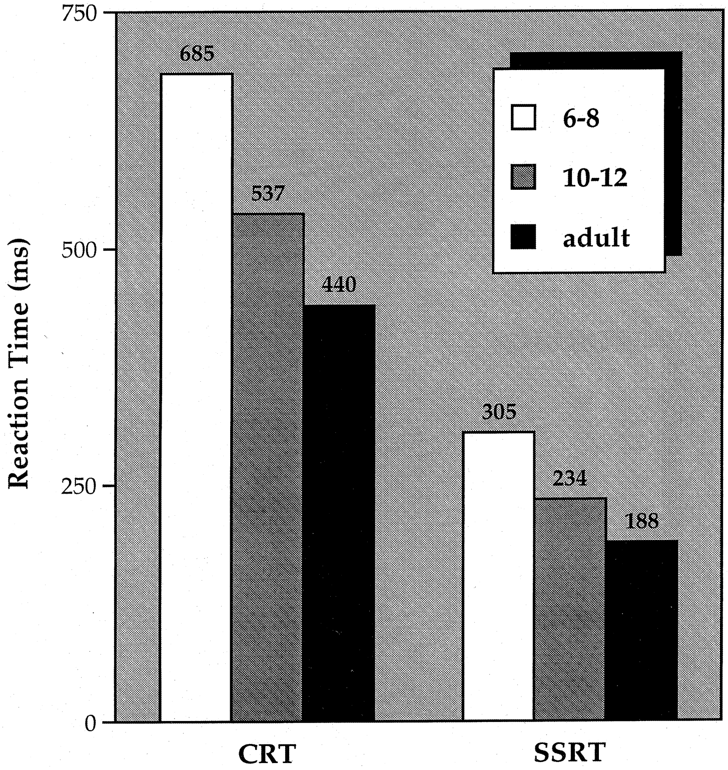

Fig. 1. Mean CRT and stop-signal reaction times (SSRT) per age group.

decrease in CRT: CRTs and SSRTs of 6–8-year-olds were 1.56 and 1.63 times slower than those of young adults, respectively; CRTs and SSRTs of 10–12-year-olds were 1.22 and 1.25 times slower than those of adults.

Thus, in contrast to the statistical results of previous developmental studies (Band, 1997; Oosterlaan, 1996; Schachar & Logan, 1990), the present results provide a convincing demonstration of developmental improvement in the ability to inhibit a response in a stop task. The discrepancy between the present observation and the findings reported in previous developmental studies using stop tasks seems to rest primarily on a difference in numbers of subjects, rather than on the magnitude of the age trends. Whereas the preceding studies all reported age trends in SSRT, these trends failed to reach statistical significance. Inspection of the numbers of subjects suggested that lack of statistical power might have prevented these age trends to become evident. When we increased the number of subjects substantially, SSRT was found to be just as sensitive to age-related improvement as was CRT.

It should be noted that this result could be interpreted to reflect a generalized effect of age on speed, rather than a specific effect on response inhibition. If an increase in age has a general influence on the speed of information processing, irrespective of the nature of specific processes, then this effect would be expressed in the speed of all processes to the same proportional extent. Thus, the global-difference hypothesis, that has recently become popular in the developmental and aging literatures, would predict SSRT to be equally sensitive to age-related improvement as CRT, and this is exactly what we observed. Although an elaborate discussion of the debate between proponents and opponents of the global-difference hypothesis is beyond the scope of the present article (for reviews see van der Molen & Bashore, 1994; see also Kramer, Hahn & Gopher, 1999; Ridderinkhof & van der Molen, 1997), we examined our data further to determine whether the present age-related decrease in SSRT is a manifestation of a general speeding effect or an effect specific to the maturation of response-inhibition processes.

If the age trends in SSRT and CRT both are the result of generalized speeding, then they should be correlated: relatively fast individuals should have fast CRTs as well as fast SSRTs, and relatively slow SSRTs should be associated with relatively slow CRTs. Thus, interindividual diversity in SSRT should correspond to that in CRT: the proportion of the between-subjects variance in SSRT that is explained by age should be (almost) eliminated if the age-related variation in CRT is partialled out. If not, then age has additional effects on SSRT over and above those on CRT. Hierarchical (linear) regression analysis showed that age explained a significant 20.2% of the variance in SSRT ($F(1,140) = 34.67, p = 0.0001$); when we partialled out the age-related variance in CRT, this proportion was reduced to 19.2%. Thus, controlling statistically for interindividual variability in CRT hardly affected the percentage of variance in SSRT explained by age. Apparently, the observed age trends in SSRT and CRT were not driven by a single generalized age effect on processing speed. Hence, we interpret the effect on SSRT to reflect a specific age-related change in the ability to inhibit one's action when so prompted by an event in the external environment.

3. Stimulus-response correspondence effects

By analogy to the observation that age-related individual differences in inhibitory control are expressed in SSRT, primary-task manipulations that vary the demands on inhibitory control may also be argued to affect stop task performance. If the stop processes as well as the primary-task processes involve the suppression of responses, one may affect the other, or vice versa, or both. One class of factors that are often argued to involve response suppression is formed by stimulus-response (S-R) correspondence effects. S-R correspondence relations can be varied in several ways (see Ridderinkhof, 1997). For our present purpose, the most relevant correspondence relation is that between irrelevant stimulus aspects and response (S_i-R correspondence).

S_i-R correspondence effects occur when, in addition to directional or symbolic target information that designates the response side, stimuli also contain irrelevant information that should be ignored but is nonetheless associated with a particular response side. Thus, S_i-R correspondence refers to conditions in which irrelevant stimulus aspects are associated with the side of the response as designated by the target stimulus aspect (e.g. when a left-pointing target arrow that requires a left-hand response is positioned to the left, or is surrounded by left-pointing distractor arrows). In S_i-R noncorresponding conditions, irrelevant stimulus aspects are associated with the side opposite to the response that is designated by the target stimulus aspect (e.g., when a left-pointing target arrow requiring a left-hand response is positioned to the right, or is surrounded by right-pointing distractor arrows). In the present study, we will examine the S_i-R correspondence effects induced by distractor stimuli. These correspondence effects are in many respects similar to the spatial correspondence effects induced by irrelevant location (typically referred to as Simon effects; see Simon, 1990, for a review), but there are some noteworthy differences (see Ridderinkhof, 1997, for an elaborate discussion). Generalizability of the correspondence findings will be addressed in the general discussion.

Response speed is typically decreased in S_i-R noncorresponding compared to corresponding conditions. In the case of S_i-R correspondence effects produced by distractor stimuli, this effect is thought to be due, on one hand, to a perceptual conflict that arises when target and irrelevant stimulus elements compete for identification, and on the other hand to a response competition that arises when irrelevant stimulus elements succeed in activating the incorrect response (e.g. Eriksen & Eriksen, 1974; Gratton, Coles & Donchin, 1992; Ridderinkhof, van der Molen & Bashore, 1995). It is often assumed, even though independent evidence has not yet been obtained, that resolving this response competition involves an active suppression of the response activation induced by the irrelevant stimulus elements (cf. Eriksen & Schultz, 1979; Gratton et al., 1992; Kopp, Rist & Mattler, 1996; Ridderinkhof et al., 1995, 1996; Smid, Mulder & Mulder, 1990; for alternative views see Logan, 1980; Phaf, Heijden & Hudson, 1990).

This selective suppression of an inappropriate response may interact with the nonselective stopping of any and all responses, such as required by a stop-signal in a stop task, when both are engaged at the same time. Recently, Kramer et al. (1994) reported an observation of an interaction between stopping and S_i-R correspondence effects in the Eriksen flanker task: SSRT increased (and the probability to inhibit given a stop-signal decreased) when to-be-ignored letter stimuli were associated with the response opposite rather than identical to that designated by the target letter. This finding provides a yet unique example of an effect of primary-task processes on stop processes, one that suggests that stopping and S_i-R correspondence effects have some inhibitory mechanism in common. In part II of the present study, we set out to replicate and extend this observation, and examine the mechanisms involved in the interaction between response inhibition in the stop task and the suppression of responses activated by irrelevant information.

3.1. Method

Subjects. Subjects in all age groups took part in the single-arrow stop task presented in the preceding section. In the same experimental session, the 48 adult subjects participated also in the S_i-R correspondence task. For reasons of comparability between the age groups in the analysis of age differences, the adult subjects were first administered the single-arrow task before taking part in the S_i-R correspondence task.

Apparatus, stimuli, tasks, and procedure. Apparatus, stimuli, and procedures were identical to those described in part I, unless specified otherwise below. In the S_i-R correspondence task (henceforth referred to as the flanker task), the target arrow was flanked by four to-be-ignored arrows (flankers), two on each side. The flankers subtended 1.03° of arc horizontally and vertically, whereas the target arrow was slightly smaller (0.83° of arc). The horizontal array of five arrows covered a visual angle of 5.80° of arc. The subjects were instructed to ignore the flankers and issue a right-hand response to a right-pointing target arrow, and vice versa. Flankers could point either in the direction corresponding to the response designated by the target (S_i-R correspondence) or in the opposite direction (S_i-R noncorrespondence). S_i-R corresponding and noncorresponding trials were intermixed randomly but equiprobably within blocks of trials.

Each subject completed six blocks of trials in the flanker task. The first two blocks were practice blocks, consisting of 40 trials each; the other four were experimental blocks, consisting of 98 trials each, the first two trials of which in each block were used as warm-ups and were excluded from data analysis. This resulted in a total of 48 experimental stop-signal trials in the experimental phase for each condition (S_i-R correspondence versus noncorrespondence).

3.2. Results and discussion

Mean CRTs for correct responses on no-signal trials, error percentages on no-signal trials, and SSRTs were submitted to an ANOVA with S_i-R correspondence as a within-subjects factor. As can be seen in Fig. 2, CRT was strongly affected by the S_i-R correspondence relation: 460 vs 520 ms in S_i-R corresponding compared to noncorresponding conditions ($F(1,47) = 339.99$, $p < 0.001$), replicating the typical pattern in the literature. Accuracy was influenced by S_i-R correspondence in the same direction (99.2 vs 91.1% in S_i-R corresponding and noncorresponding conditions, respectively; $F(1,47) = 50.08$, $p < 0.001$), suggesting that the CRT results could not be explained by a trade-off between speed and accuracy.

Interestingly, the S_i-R correspondence relation affected SSRT as well: as shown in Fig. 2, SSRT was 182 vs 208 ms in S_i-R corresponding and noncorresponding conditions, respectively ($F(1,47) = 39.69$, $p < 0.001$). The stop processes were completed more slowly when flankers were associated with the incorrect response, replicating a similar finding reported by Kramer et al., 1994 using a different type of stimuli. The S_i-R correspondence effect in the primary task was argued above to involve an active suppression of the response activation induced by the flankers; this selective inhibition in the primary task may interfere with the nonselective stopping of any and all responses, as required by stop-signals in the stop task, when both are engaged at the same time. However, if response inhibition in the stop task is affected by response inhibition in the primary task, the reverse influence may also be present: the engagement of response inhibition in the stop task may in turn affect the efficiency of response inhibition in the primary task. This influence may be examined

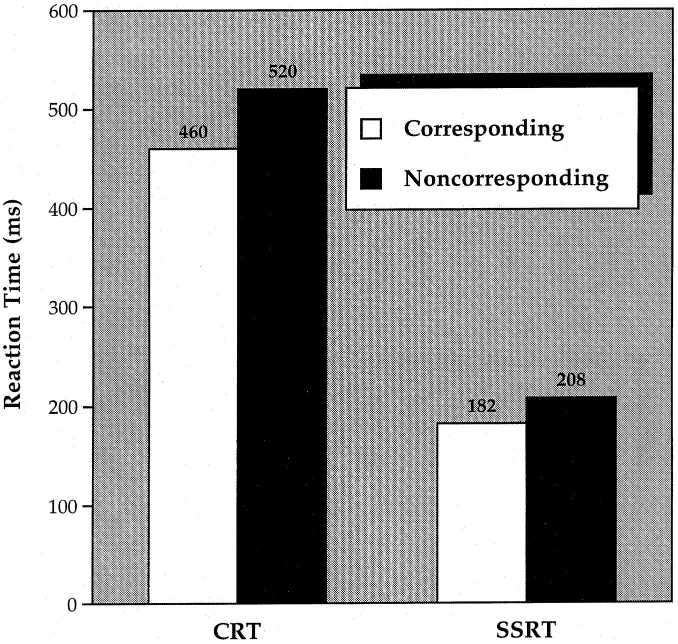

Fig. 2. Mean CRT and SSRT in S_i-R Corresponding (white bars) and Noncorresponding conditions (black bars).

indirectly by comparing CRT between trials with and without stop-signals. If the response inhibition going on in the stop process affects the suppression of incorrect responses in the S_i-R noncorrespondence condition of the flanker task, then the latter suppression should be less efficient (and hence CRT should be slower) in trials where a stop-signal calls for response inhibition compared to trials where no stop-signal is presented and response inhibition is not invoked. By contrast, S_i-R corresponding trials do not require suppression of incorrect responses, and hence CRT should not depend on the presence or absence of a stop-signal and the response inhibition associated with such a signal.

CRTs in stop-signal trials can only be inspected for the faster part of the CRT distribution, that is, for those primary task responses that were fast enough to escape the inhibition called for by the stop-signal. Thus, to compare CRT in stop-signal trials and no-signal trials, only that part of the CRT distribution of no-signal trials that corresponds to the known portion of the CRT distribution of stop-signal trials should be examined (cf. Jennings, van der Molen, Brock & Somsen, 1992). Fig. 3 shows that, compared to CRT in this truncated portion of the no-signal CRT distribution, CRT in stop-signal trials was slower, but this effect was far more drastic in S_i-R noncorresponding trials (50 ms) then in corresponding trials (11 ms; $F(1,47) = 33.60, p < 0.001$). Thus, when stop processes were activated by a stop-signal (even though they lost the race), CRT was slower than when stop processes were not activated (in the absence of a stop-signal). The presence of a stop-signal delayed the

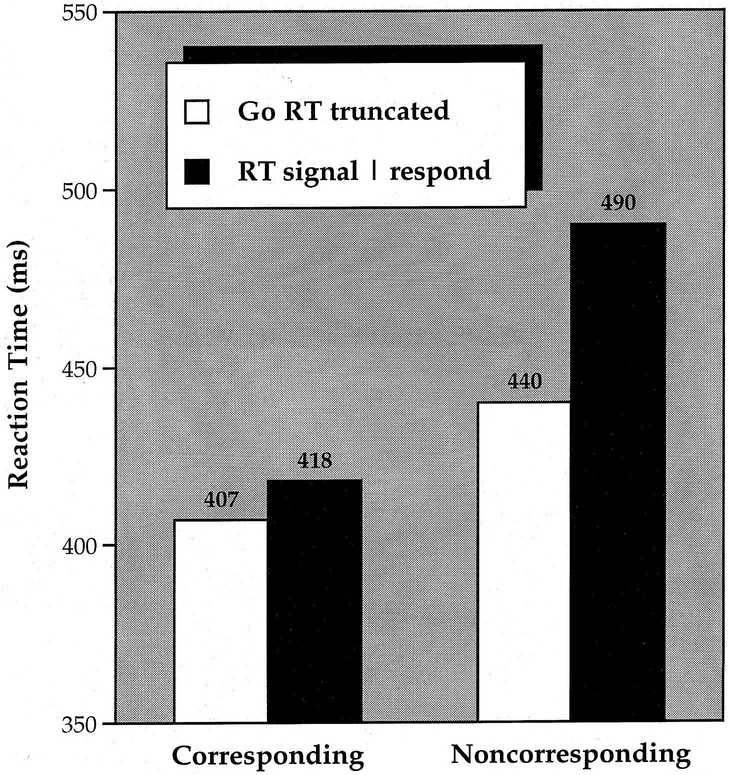

Fig. 3. Mean choice reaction times in stop-signal trials (black bars) and in the corresponding portion of the non-signal RT distribution (white bars) in S_i-R Corresponding and noncorresponding conditions.

primary-task response only marginally when that response corresponded to the side indicated by the flankers, but substantially when flankers activated the incorrect response. This finding suggests that response suppression in the primary task was less efficient when stop processes were active concurrently. Hence, the interaction between response inhibition in the primary-task and stop processes can be inferred to be bidirectional rather than unidirectional.

A final analysis was carried out to address the question of whether individuals who performed efficiently with regard to one type of response suppression were also efficient in performing the other type of response suppression. That is, did the selective suppression of inappropriate responses (as activated by noncorresponding flankers) and the nonselective suppression of responses (as called for by a stop-signal) covary within subjects? Correlation analysis indicated that the S_i-R correspondence effects on CRT and SSRT displayed a moderate correlation of 0.55 ($t(47) = 4.41, p < 0.001$). One possible account for this finding is, once more, in terms of individual differences in general processing speed: if the speed in general of the primary-task and stop processes were correlated positively, then the correlation between *effect sizes* on CRT and SSRT might be an epiphenomenon of the correlation between *overall* CRT and SSRT. In the present data, however, overall CRT and SSRT were not correlated positively (in fact, a negative correlation of -0.29 just reached significance; $t(47) = 2.08$, $p = 0.043$), ruling out an interpretation in terms of processing speed in general. Instead, the positive correlation between the S_i-R correspondence effects on CRT and SSRT may be taken to lend support to the notion of mutual influences between response inhibition in the primary-task and response inhibition in the stop process. If stopping and S_i-R correspondence effects involve a common inhibitory mechanism, or, alternatively, involve separate inhibitory mechanisms that compete for activation, then they should be correlated positively.

4. General discussion

The primary aim of the present study was to identify factors that influence inhibitory aspects of adaptive behavior. The ability to suppress one's actions was examined using a stop task, which provides a useful measure of the efficiency of response inhibition in the form of SSRT (Logan, 1994; Logan & Cowan, 1984). Two factors that were hypothesized to influence the ability to stop were examined: the effects of irrelevant information, and the effects of age.

4.1. The effects of age

The relatively late functional maturation and relatively early deterioration of the frontal lobes (and in particular prefrontal cortex) suggest that inhibitory control processes are compromised in children and older adults (see van der Molen & Ridderinkhof, 1998, for a review). In developmental studies, however, significant age changes in SSRT have not been reported, presumably due to lack of statistical power. To determine whether or not SSRT decreases as children grow older, in the present study we administered a stop task to large groups of children and adults. The results provide a clear-cut demonstration of developmental improvement in the ability to inhibit a response: SSRT was found to be just as sensitive to age-related improvement as was CRT. However, the age trends in CRT and SSRT were not the result of a single generalized speeding factor; age contributed a proportion of variance in the speed of stopping that was unique to SSRT (and not shared with CRT).

The present outcome is consistent with the results of the study by Kramer et al. (1994), who demonstrated an age-related decrease in the ability to stop in older compared to young adults. Our results are supported also by the results of a life-span developmental study that was conducted at approximately the same time as the present study (Williams, Ponesse, Logan & Tannock, in press). Williams et al. report that in subjects ranging in age from 5 to 81 years old, SSRT decreases as children grow older and then again increases as adults enter the later stages of life. Thus, even though subjects in all age groups were capable of inhibiting their responses (see also Kramer et al., 1994), SSRT appears to provide a suitable measure to reflect maturational changes in inhibitory control processes. The observed age-related differences in SSRT are in agreement with the general notion, derived from the cognitive neurosciences, that the special role for the frontal brain in biological maturation and senescence is expressed in developmental growth and decline in processes of cognitive control. A substantial literature suggests that age-related change in inhibitory control can be observed in performance on a wide variety of cognitive tasks, and the present study of adaptive behavior contributes to this literature by demonstrating that the efficiency of response inhibition in a stop task increases as children grow older.

Developmental growth in inhibitory control over interference from irrelevant information, irrelevant strategies, or irrelevant responses has been invoked to explain age-related change in performance on a wide variety of cognitive tasks (e.g. Dempster, 1992, 1993; Shimamura, 1995). Although the term inhibitory control has been used for a wide array of phenomena (e.g. Dagenbach & Carr, 1994), all inhibitory behaviors do not necessarily change in concert. Recent evidence challenges the notion that inhibitory control is unitary or unidimensional, and that age-related inhibitory deficiencies are general in nature. Different forms of inhibition that are believed to be mediated by different parts of the brain (or even different subregions within the frontal brain) accordingly may display different patterns of age-related inhibitory deficiencies (e.g. Kok & Talsma, 1997; Kramer et al., 1994; Ridderinkhof & van der Molen, 1997; West, 1996).

4.2. Stimulus-response correspondence effects

To the extent that not only stop processes, but also primary-task processes involve the suppression of responses, we predicted that the two sets of processes would interact with one another. That is, primary-task manipulations that vary the demands on inhibitory control were anticipated to affect stop task performance. To evaluate this hypothesis, we examined SSRT under different levels of S-R correspondence in the primary task. S_i-R correspondence relations were varied in the present experiment to examine the mechanisms involved in the interaction between response inhibition in the stop task and the suppression of responses activated in S_i-R noncorrespondence conditions.

S_i-R correspondence was manipulated through the use of distractor stimuli: irrelevant flanking arrows were associated with the same or opposite response as that designated by a target arrow. When noncorresponding flankers activate an incorrect response, this activation calls for active suppression in order to prevent the execution of an inappropriate overt response (e.g. Gratton et al., 1992; Kopp et al., 1996). This selective suppression could be hypothesized to interact with the nonselective response inhibition required by a stop-signal in the stop task, when both are engaged concurrently. Indeed, SSRT was affected by the primary task S_i-R correspondence relation: the stop processes were completed slower when flankers were associated with the incorrect response. This observation provides a replication of the finding reported by Kramer et al. (1994), but this time with arrow arrays rather than letter arrays (in fact, the effect size was approximately equal to that found in the Kramer et al. study).

The present pattern of findings was obtained by varying the correspondence relations between distractor stimuli and the response. Correspondence effects can also be obtained by varying the correspondence relations between the irrelevant location of the stimulus and the side of the response required by that stimulus (as in the Simon task). Although theoretical accounts of the Simon effect (e.g. Hommel & Prinz, 1997; Kornblum et al., 1990; Lu & Proctor, 1995) are to some extent similar to accounts of distractor effects (e.g. Gratton et al., 1992; Ridderinkhof et al., 1995), these types of correspondence effects are different in some important respects (for a discussion see Ridderinkhof, 1997). For instance, whereas there appears to be some consensus that the Simon effect does not involve a perceptual conflict (see Lu & Proctor, 1995, for a review), perceptual conflict is generally argued to play a role in distractor effects (e.g. Coles et al., 1985). More important, in Simon tasks, correspondence effects are largest in fast response quantiles, but diminish in slower response quantiles (de Jong, Liang & Lauber, 1994) because the activation of the response code triggered by the irrelevant location decays rapidly (e.g. Hommel, 1994). However, the opposite pattern is observed with distractor effects (Ridderinkhof & van der Molen, 1993): The size of correspondence effects increases from early to late response quantiles. As a consequence, the influence of S_i-R noncorrespondence on SSRTs would likely be overestimated in Simon tasks, whereas they may be somewhat underestimated in the present distractor task (because the stop process has already won the race by the time the noncorresponding distractors reach their maximum interference effect, in slow trials).

Osman et al. (1986) argued that repetition of S-R pairs affected a stage in the primary-task process that so closely preceded the overt response that this response could no longer be countermanded by a stop-signal. An effect on "ballistic" stages of the reaction process also affects the estimated value of SSRT (see Band, 1997; Osman et al. did not compute SSRT). By analogy, the present finding of on S_i-R correspondence effect on SSRT could have resulted not from an influence on the stop process, but from an influence on the ballistic stage of the primary task. If so, we would not be looking at interactions between inhibitory mechanisms in stop and primary-task processes. However, according to the literature discussed above, S_i-R correspondence relations do not exert their effects on the duration of ballistic processes. ERP analyses have shown that if noncorresponding flankers succeed in activating an incorrect response, this activation can typically be countermanded before it turns into complete execution (as indicated by ERP data; see, e.g. Gratton, Coles, Sirevaag, Eriksen & Donchin, 1988; Kopp et al., 1996; Ridderinkhof, Lauer & Geesken, 1996; Ridderinkhof & van der Molen, 1995). Thus, the present influence on SSRT is thought to derive from an effect on the stop process, not on the ballistic stage of the primary-task process.

In briefly discussing a possible mechanism underlying their observation of an S_i-R correspondence effect on SSRT, Kramer et al. suggested that an increase in the number of activated responses (as with S_i-R noncorresponding stimuli) is associated with a decrease in the speed of inhibitory control in the stop process. In other words, it takes longer to suppress the activation of two responses than the activation of one response. Closely related to this account, one might argue that an increase in the total amount of response activation is associated with a decrease in the speed of stopping. Thus, the activation of an incorrect response on the basis of irrelevant information (as induced by S_i-R noncorresponding stimuli) may result in an increase in both CRT and SSRT. These accounts make the assumption that the interaction between primary-task and stop processes are unidirectional: the additional response activation produced by S_i-R noncorresponding flankers in the primary task yields a delay of the finishing time of the stop process.

Alternatively, the S_i-R correspondence effects on SSRT may be interpreted to reflect an interaction between the *suppression* of an inappropriately activated response (rather than the *activation* of this response) with the stop process. We argued that if the selective inhibition of the response activation induced by the flankers in the primary task interferes with the concurrent nonselective response inhibition in the stop task, then the operation of response inhibition in the stop task may in turn affect the efficiency of response inhibition in the primary task. We examined this reverse influence by comparing CRT in trials with and without stop-signals: the suppression of incorrect responses in the flanker task should deteriorate when, concurrently, response inhibition is engaged in the stop process. Indeed, in S_i-R noncorresponding trials, CRT was found to be slower in stop-signal trials where a stop-signal called for response inhibition compared to trials where no stop-signal was presented and response inhibition was not invoked. Hence, we conclude that the interaction between response inhibition in the primary-task and stop processes is bidirectional, not unidirectional.

To account for this pattern of findings, and consistent with the theoretical considerations presented in the introductory sections, the operation of response inhibition in the primary-task processes and response inhibition in the stop process may be assumed to affect one another negatively. For instance, the suppression of a response occurring in the context of one set of processes may have to wait in queue for the response suppression already taking place in the context of the other set of processes. Or, when response suppression occurs in the primary-task and stop processes concurrently, the two may compete for activation, either in a capacity-sharing fashion or in a capacity-independent fashion (for a discussion see Bundesen, 1993), resulting in a reduced efficency of response suppression in both. In support of this account in terms of mutual influences between response inhibition in the primary-task and response inhibition in the stop process, S_i-R correspondence effects on CRT and SSRT were correlated positively, indicating that individuals that were 'good inhibitors' in the primary-task processes were also good inhibitors in the stop processes.

4.3. Mechanisms of response inhibition

One further issue to be addressed pertains to the extent to which the inhibitory mechanisms involved in stopping and selective response suppression share common grounds. Recent theories of motor control (e.g. Brooks, 1986; Bullock & Grossberg, 1991) suggest that responses are selected and prepared by cortical processes whereas midbrain processes control a peripheral GO signal to release (or arrest) any prepared movement. Consistent with these assumptions, Jennings and colleagues observed an interaction between cardiac inhibition and response inhibition and suggested that the midbrain system that exerts vagal control over heart rate also controls response inhibition by intercepting cortical motor commands (Jennings et al., 1992). De Jong and co-workers (de Jong et al., 1990, de Jong, Coles, Logan, 1995) found the peripheral (midbrain) mechanism to be *nonselective*, in that any and all responses were inhibited. In addition, on the basis of electrophysiological evidence they suggested a separate central (cortical) mechanism that *selectively* inhibits central response preparation processes.

Thus, the selective inhibition of irrelevant responses as activated by to-be-ignored stimulus elements may involve the cortical inhibition mechanism whereas the nonselective stopping of any and all responses, such as required by a stop-signal in the stop task, may involve the midbrain inhibition mechanism. However, in a comprehensive survey of the cognitive-neurosciences literature, Band and van Boxtel (1999) concluded that the notion that some midbrain structure is responsible for nonselective response inhibition is not compelling. Instead, they took evidence that they reviewed to support the notion that responses are held in check through inhibitory control, exercised by an executive system (located in prefrontal cortex) that supervises the flow of information through subordinate mechanisms (cf. Logan & Cowan, 1984; Stuss, 1992). Manifestations of inhibitory control can occur anywhere in the system (for instance in primary motor cortex, but also upstream from it, or downstream). Response inhibition can be selective or general, depending on where in the system the effect is exerted.

Thus, although the types of response suppression examined in the current study may have different loci of effect, they may share an inhibitory mechanism in common. Hence, they interact in their effect on behavior. The present developmental findings are also in agreement with a conception in which a prefrontal executive mechanism is in command of inhibitory control (as an instrument of adaptive goal-directed behavior). As illustrated, the prefrontal control system does not mature fully until late in ontogenetic development (cf. van der Molen & Ridderinkhof, 1998); hence the efficiency of inhibitory control over unwanted responses improves with as children grow older, as expressed in the age-related decrease in SSRT.

Acknowledgements

The research of Dr. Ridderinkhof has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences. We are thankful to Marlies van Gelderen, Anouk Koppen, Diane Lennertz, Sharon Lie-A-Tsoen, and Judy Moester for their efforts in collecting the data. Address correspondence to the first author at the Department of Developmental Psychology, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, the Netherlands.

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