Perspectives on stopping behavior : process analyses of stop-signal inhibition

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5 Stages of inhibitory processing: The additive factor method on stop-signal inhibition

Abstract

The main purpose of this study was to identify stages in the stop process by using experimental manipulations that have been afforded by the AFM paradigm. First, a standard AFM design was used to confirm additive effects of signal discriminability (high vs. less) and stimulus-response compatibility (SRC, compatible vs. incompatible) impinging on separate stages of the go-reaction process. The go signals used in the standard AFM tasks then served as stop signals in the selective stopping tasks. Subjects were instructed to discriminate between two visual stop signals, and to inhibit their primary-task response upon the presentation of spatially compatible stop signals only, or to spatially incompatible stop signals only. Analyses of stopping latencies showed that selective stopping to incompatible stop signals was slower than stopping to compatible stop signals. Stop-signal discriminability systematically affected selective stopping speed, but only in a subgroup of participants. In conclusion, an obtained additive relation between (stop-) signal discriminability and (stop-) SRC on stopping latency confirmed that the stopping process can be decomposed into two distinct stop-signal processing stages.

5.1 Introduction

5.1.1 Stopping as extreme cognitive control

The ability to withhold and interrupt ongoing or planned actions in response to sudden changes in the environment is important for cognitive ('executive') control and a prerequisite for adaptive and goal-directed behavior. Since the formal operationalization of the *stop-signal paradigm*, about two decades ago by Logan and Cowan (1984) many researchers operating in various theoretical frameworks have adopted the stop task as an experimental tool to investigate inhibitory motor control (see Logan (1994) for a review). In the stop task, participants perform on a go task, usually a speeded choice reaction task requiring the binary choice discrimination of two visual signals by manually pressing one of two response buttons. Shortly after the onset of the go signal, participants are occasionally presented with a stop signal (usually a tone) that instructs them to withhold the response. The interval between the onset of the go signal and the presentation of the stop signal (or stop-signal delay) is under experimental control, enabling the experimenter to manipulate the probability of successful response inhibition on a given stop trial. Stopping is easy when the stop signal is presented early, but difficult, or virtually impossible when it is presented late vis-à-vis the respond signal (e.g., Lappin & Eriksen, 1966; Logan, 1994; Logan & Cowan, 1984).

5.1.2 Studies with the stop-signal paradigm

Logan and colleagues have conceptualized performance in the stop-signal paradigm in terms of a horse race between go processes versus stop processes that run for completion and operate independently. The go processes are initiated by the onset of the go signal, whereas the onset of the stop signal starts the stopping processes. Whether or not the go response will occur depends on the outcome of the race. If the go process wins, a response is produced despite the presence of a stop signal, whereas the response is successfully inhibited when the stopping process wins the race. One of the virtues of the horse-race model is that, with a small set of formal assumptions, it provides a method to estimate the stopping latency, stop-signal reaction time or SSRT as an internal inhibitory response to the stop signal. Several reports in the stopping literature indicate that SSRT appears to be rather invariant across tasks and typically amounts to values between 200 or 250 ms for healthy young-adults (see Logan, (1994) for a review). Among the various responses whose stopping properties have been investigated are manual responses (e.g., Logan, 1981), speech (Ladefoged, Silverstein, & Papcun, 1973), typing (Logan, 1982; Long, 1976; Rabbit, 1978), foot movements (De Jong, Coles, & Logan, 1995), and eye movements (Logan & Irwin, 2000; Hanes & Carpenter, 1999). Somewhat prolonged stopping latencies have been reported for children (Bedard et al., 2002; Ridderinkhof, Band, & Logan, 1999; Van den Wildenberg & van der Molen, 2003a) and older adults (Christ, White, Mandernach, & Keys, 2001; Kramer, Humphrey, Larish, & Logan, 1994; Williams, Ponesse, Schachar, Logan, & Tannock, 1999).

In clinical settings, the stop-signal paradigm has been used successfully to distinguish between normal children and children diagnosed with attention deficit hyperactivity disorder (ADHD; Schachar & Logan, 1990). ADHD children exhibited less efficient stopping than children diagnosed with other psychopathologies and normal control children (Jennings, van der Molen, Pelham, Brock, & Hoza, 1997; Oosterlaan, Logan, & Sergeant, 1998; Oosterlaan & Sergeant, 1995; Overtoom et al., 2002; Schachar & Logan, 1990; Schachar, Mota, Logan, Tannock, & Klim, 2000; Van der Schoot, Licht, Horsley, & Sergeant, 2000; for reviews of ADHD studies with the stop-signal paradigm see Nigg, 2001). Stopping latencies improved after administration of the stimulant drug Methylphenidate compared with administration of a placebo in children with ADHD (Tannock, Schachar, Carr, Chajczyk, & Logan, 1989). Others have reported negative effects of alcohol op stopping latency within the normal population (Mulvihill, Skilling, & Vogel-Sprott, 1987).

5.1.3 The nature of stopping

Because of its generality, the horse-race model usually fits behavioral data obtained in the stop-signal paradigm very well. However, it does not provide a deeper understanding of the nature of the stopping process. Research aimed to disentangle the nature of the stopping processes itself can broadly be divided into three perspectives. First, several studies have focused on the interaction of stopping with other forms of inhibition. A second route involves complicating the standard stop paradigm. Finally, psychophysiological and brain imaging studies have extended our understanding of the neural substrates that underlie motor inhibition.

The first strategy to investigate stopping processes focuses on stopping in relation to other forms of inhibition. Several investigators factorially combined stopping with experimental manipulations that draw upon a form of inhibitory control as well, to learn more about stopping from the possible interaction patterns. Logan (1981), for example, observed that stopping latency is approximately equal for spatially compatible and incompatible manual responses (see Logan & Irwin (2000) for a recent replication). Apparently, stopping does not interact with the ability to resolve the conflict between the prepotent compatible response and the spatially incompatible response (e.g., Kornblum, Hasbroucq, & Osman, 1990). Others crossed stopping with the inhibition of responses to target stimuli flanked by task-irrelevant distracters assigned to the same or to the opposite response (Kramer et al., 1994; Ridderinkhof et al., 1999). These investigators found that responses to targets flanked by incongruent distracters were more difficult to inhibit than responses to congruent displays. This pattern of results was interpreted to suggest that stopping and the need to inhibit the (incorrect) response to incongruent flankers compete for execution (cf. Ridderinkhof et al., 1999). Finally a similar strategy by crossing stop-signal inhibition during different levels response readiness has been applied by Van den Wildenberg, van der Molen, and Logan (2002). Subjects performed a primary task requiring a speeded binary choice reaction on go trials and response inhibition on nogo trials. An occasional cue informed subjects that a nogo trial was imminent but left them uncertain about the number of go trials separating the cue and the upcoming nogo trial. When subjects were anticipating a nogo signal, stopping was delayed compared to a control condition. This pattern of findings was interpreted with reference to a response readiness model suggested by Mattes, Ulrich, and Miller (1997; see also Ulrich, Mattes, & Miller, 1999).

Second, other researchers have examined stopping processes in greater detail by complicating the stopping process (see Logan, 1994). For example, some investigators examined stopping in a change paradigm by asking subjects to stop one response and execute another (Logan & Burkell, 1986). It was observed that the duration of stopping is somewhat longer when it has to be followed by the execution of another response than when it is not. Other investigators examined selective stopping at the perceptual end of stop-signal processing, by presenting their subjects with two tones – a valid stop signal, instructing the subject to stop the primary-task response and an invalid stop signal requiring the subject to execute the go response as planned. These selective stopping studies indicate that the duration of the stop process is lengthened when subjects have to stop their response to one of two stop signals but not to the other (Bedard et al., 2002; Riegler, 1986). Finally, selective inhibitory control has been examined at the motor end of stop-signal processing by asking subjects to inhibit only one response (e.g., the left hand) but not the other (e.g., the right hand) upon a stop signal. The results showed that subjects are able to stop selectively (De Jong et al., 1995; Logan, Kantowitz, & Riegler, 1986). De Jong et al. reported slowing of primary-task RTs even when the response should not be inhibited, and the detrimental effect of such interference was stronger when the primary-task stimulus was degraded. In addition, degrading relative go-signal discriminability was observed to hamper the speed of selective stopping of critical responses compared to highly discriminable go signals (De Jong et al., 1995, Exp. 2).

Third, several psychophysiological studies examined the neural substrates of stopping. The *lateralized readiness potential* (LRP) in combination with electro-myographic (EMG) measures led De Jong and colleagues to propose two separate inhibitory mechanisms - a slower central cortical mechanism capable of selective inhibition and a peripherally operating midbrain mechanism for fast non-selective or simple stopping (De Jong, Coles, Logan, &

Gratton, 1990; De Jong et al., 1995). The notion of a peripheral inhibition mechanism has been linked with results obtained from cardiac studies by Jennings, van der Molen, Brock, and Somsen (1992). These researchers report that successful inhibition of a motor response was associated with heartbeat slowing (deceleration), whereas failed inhibitions were not. The fact that cardiac inhibition and motor inhibition interact has been interpreted to suggest that both are controlled in part by the same midbrain system. However, based on a review of psychophysiological data in the stop-signal literature, Band and van Boxtel (1999) formulated an alternative interpretation of the neural mechanisms involved in stopping. Their main point was that a peripheral stopping mechanism is incorrectly inferred from the psychophysiological data. Alternatively, Band and van Boxtel suggested a model in which an integrated circuit of the prefrontal cortex and basal ganglia are candidate agents of response inhibition, whereas possible effect sites of inhibition are the thalamus and motor cortex (Brunia, 1993; Eimer 1993; Goldberg 1985; Jodo & Kayama, 1992; Kok, 1986; Naito & Matsumura, 1994; Pfefferbaum, Ford, Weller, & Kopell, 1986; Van Boxtel, van der Molen, Jennings, & Brunia, 2001). Brain imaging techniques (Pliszka, Liotti, & Woldorff, 2000; Rubia et al., 2001) and microelectrode studies (Kawashima et al., 1996; Sasaki & Gemba, 1986; Sasaki, Gemba, Nambu, & Matsuzaki, 1993) have also have provided support for the prefrontal substrate of inhibitory processing. Single-cell recordings in primates performing on a stop task provide another psychophysiological approach towards a better understanding of the nature of inhibition. Hanes and colleagues recorded unit activity in the frontal eye fields during the countermanding of eye movements and identified single-cell signatures of inhibitory visuomotor control (Hanes, Patterson, & Schall, 1998; see Logan & Irwin, 2000, for a behavioral study comparing inhibitory control of eye and hand movements).

5.1.4 The additive factor method (AFM)

The goal of the current study was to investigate the nature and more specific the architecture of stop-signal processing, by adopting the theoretical framework of the *additive factor method* (AFM; Sternberg, 1969). The AFM is an elaborate procedure fore examining components of reaction processes. In the study of human information processing, the AFM has been applied successfully to distinguish serial mental processing stages in reaction-time (RT) tasks by means of experimental factors (Sternberg, 1969). Choice RT is taken as the sum of time taken by a set of sequentially ordered and independent processing stages (Sternberg, 1969). The AFM aims at the selective manipulation of the duration of these processing stages to elucidate the architecture of cognitive processes. According to AFM-logic, different experimental factors that affect different processing stages must have additive effects on RT measurement. Conversely, if the effects on RT interact, the factors are inferred to affect at least one common stage (for reviews of AFM studies see Sanders, 1990; 1998; Van der Molen, Bashore, Halliday, & Callaway, 1991).

For example, a large body of AFM studies has indicated that signal discriminability and stimulus-response compatibility (SRC) have additive effects on choice RT. According to AFM reasoning, these patterns suggest that the experimental variables of signal discriminability and SRC influence the processing latencies of two different stages, respectively a perceptual and a motor-related stage. An extensive study by Adam (2001), for example, recently confirmed that effects of two levels of stimulus-response compatibility, factorial combined

with two levels of stimulus discriminability and two levels of two levels of response repertoire all had additive effects on mean RT. This pattern of results led Adam to conclude that each variable affected a different information processing stage. Recently, the application of AFM has been extended to information processing in animals (Courtière, Hardouin, Hasbroucq, Possamaï, & Vidal, 2000; Roberts, 1997).

5.1.5 The present study

In this report the AFM, which has been used repetitively to explore stages of go-signal processing, will be used to investigate stop-signal processing in the stop-signal paradigm. Our basic assumption is that stop processes are quite similar in nature to go processes. Go signals require perceptual discrimination, translation into an appropriate action, and then the programming and unfolding of that action. Likewise, stop signals are considered to require perceptual discrimination, translation into an appropriate action (i.e., inhibition of ongoing responses), and then the programming and unfolding of that inhibitory action. The main purpose of this experiment is to identify stages in the stopping process using the experimental manipulations that have been employed to identify stages in the reaction process.

First, a standard AFM design was used to determine additive effects of signal discriminability and SRC on separate stages in the reaction process. In these tasks, subjects responded to the position of two signals represented as pupils in the eyes of a schematic face, such that the eyes looked either to the right or to the left. It was predicted that responses on blocks with compatible SRC mapping would be faster than incompatible responses. Also, it was expected that responses to blocks with high signal discriminability would be faster than responses to less discriminable signals. Finally, according the AFM logic, these two main effects are hypothesized to be additive.

Second, the same signals that have been employed in the standard AFM tasks were used as stop signals in a stop-task setting to examine processing stages of stopping. Selective stopping to one of two highly discriminable stop signals is predicted to be faster than to a less discriminable stop signal. In the compatible stopping conditions, subjects will have to inhibit the response if the stop signals are presented at the location that is compatible with respect to the response location associated with the go task (e.g., a left-hand response should be inhibited if a stop signal is presented to the left). Alternatively, the incompatible stop instruction required subjects to inhibit the go response if the stop signal appeared in the direction opposite to the response hand indicated by the go signal (e.g., a left-hand response should be inhibited if a stop signal is presented to the right). Compatible selective stopping is predicted to be faster than incompatible selective stopping (Van den Wildenberg & van der Molen, 2003a). This setup affords the decomposition of stopping process by anticipating an additive relation between (stop-) signal discriminability and (stop-) SRC on selective stopping latency.

5.2 Experiment I

5.2.1 Method

Participants

Twenty-four undergraduate students (18 females, mean age 21 years) participated to fulfill course requirements. All subjects reported to be healthy and had normal or corrected-to-normal vision.

Apparatus and signals

An IBM-compatible computer presented the signals and recorded the responses. All trials of all tasks presented a schematic face that remained on screen during the tasks (see Figure 5.1). The schematic face was drawn in black lines and presented against a light gray background at the center of a 15-inch computer monitor. The imperative signals of the *standard AFM tasks* consisted of two black circles (diameter 4 mm) that appeared as pupils in the eyes of the schematic face (illustrated in Table 5.1-A). The pupils were presented on the horizontal mid-axis of the eyes, either 4 mm to the left or right with respect to the center of the eyes (i.e., less signal-discriminability condition) or at a distance of 8 mm from the center, that is in the outer left or right canti of the eyes (i.e., high signal-discriminability condition).[1]

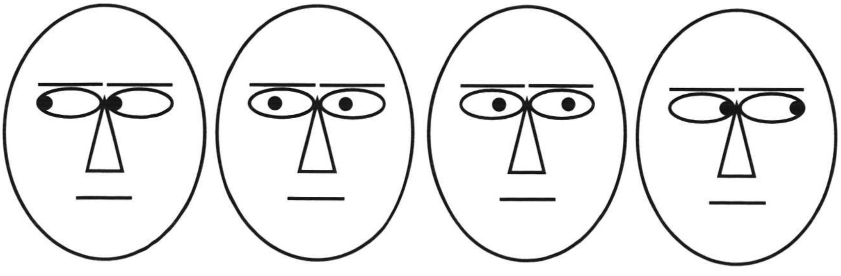


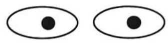
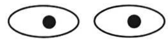
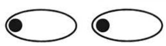
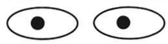
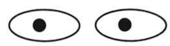
Figure 5.1: Schematic face. Subjects were instructed to execute a compatible or incompatible manual response according to the directional gaze of the eyes.

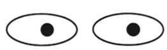
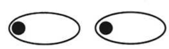
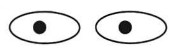
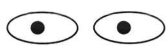
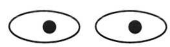
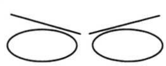
In the four *selective stop tasks*, the imperative signals of the go task (go signals) were indicated by the position of two lines located 1 mm above the eyes of the schematic face and depicted the eyebrows (see Table 5.1-B). An imperative signal was indicated by tilting the far ends or the close ends of the eyebrows from a horizontal or neutral position, representing an angry vs. a sad expression.

[1] Pluister (2003) repeatedly observed additive effects on RT using these manipulations of signal discrimination and SRC.

Imperative (eyebrow) signals were separated by intervals varying randomly and equiprobably from 1250 to 1750 ms in steps of 125 ms. The imperative signals were response terminated or terminated after 1000 ms if no key had been pressed. The 'z' and the '/' keys on the computer keyboard recorded responses with the left and right index fingers.

Table 5.1: Signals and instructions in the standard AFM (A) and stop tasks (B).

A	Signal – Response Compatibility			
	Compatible		Incompatible	
	Discriminability		Discriminability	
	High	Less	High	Less
Signals				
Instructions	"respond with the right hand"		"respond with the left hand"	
Signals				
Instructions	"respond with the left hand"		"respond with the right hand"	

B	Stop-Signal /Response Mapping			
	Compatible Stopping		Incompatible Stopping	
	Discriminability		Discriminability	
	High	Less	High	Less
Valid Stop signals				
Instructions	"stop if eyes look in the same direction as the response"		"stop if eyes look in the direction opposite to the response"	
Invalid Stop signals				
Instructions	"don't stop if eyes look in the direction opposite to the response"		"don't stop if eyes look in the same direction as the response"	
Go signals				
Instructions[a]	"respond with right hand"		"respond with left hand"	

[a]The mapping of go signal to response hand was counterbalanced across subjects.

Tasks and design

Standard AFM tasks. A schematic of the experimental conditions in the AFM tasks is shown in Table 5.1-A. The within-subjects factors of the factorial design were Signal Discriminability (high vs. less) that was defined by the distance between the two alternative stimulus positions and SRC (compatible vs. incompatible). In the compatible condition, the stimulus position (i.e., left or right) mapped directly onto the response position (left or right also), whereas in the incompatible condition the mapping was reversed so that stimuli appearing to the left required a right response, and stimuli appearing to the right a left-hand response. In the standard AFM tasks, subjects responded to the direction (left or right) of the gaze of the schematic face. Signal discriminability varied by directing the gaze slightly to the left vs. right (less discriminable) or to an eccentric left vs. right position (highly discriminable). The standard AFM tasks were presented in four blocks of 100 trials each, according to the factorial combination of two levels of Discriminability and two levels of SRC.

Stop tasks. The primary task of the four tasks was to discriminate between angry vs. sad schematic faces, according to the horizontal lines just above the eyes of the schematic face. On each trial, the eyebrows changed from a neutral position into 'angry' or 'sad' upon which subjects respectively responded by pressing the left key ('z' key on the keyboard) or the right key ('/' key on the keyboard) or vise versa as fast and as accurately as possible. On 30% of the trials, pupils in the schematic face were presented as a stop signal shortly after the onset of the primary signal upon which the response to the primary task had to be inhibited. A tracking algorithm (Levitt, 1971) was used to obtain a percentage of successful response inhibition of approximately 50%. Upon successful stopping the interval between the onset of the primary-task signal and the stop signal (or stop-signal delay) on the next stop trial was increased by 50 ms whereas upon failures to stop, stop-signal delay was reduced by 50 ms.

Four selective stop-signal tasks were administered, according to the factorial combination of Stop-signal Discriminability and Stop-SRC. As in the standard AFM tasks described above, discriminability was implemented by varying the distance between the relative positions of the pupils. Stop signals could appear equiprobably on a location that was either compatible (i.e., representing the same direction as) or incompatible (i.e., representing the opposite direction as) with respect to the response location indicated by the primary task. SRC was varied block wise by instructing participants to inhibit their response, but only if the stop signal was presented at the side of the responding hand (compatible stopping) or if the stop signal appeared on the other side of the responding hand (incompatible stopping). Consider for example a compatible stop task where angry eyebrows (\ /) are coupled with a right-hand response and sad eyebrows (/ \ ) with left-hand responses. Subjects should inhibit their primary-task response only if the eyes look at the same direction as the response. Thus, a response with the right hand to angry eyebrows should be stopped only if eyes were presented looking to the right. In the same way, following a similar go-task mapping but now with an incompatible stopping instruction: Right-hand responses to angry eyebrows associated with a right-hand response should only be actively suppressed whenever the stop pupils look to the left. Stop trials that signal response inhibition are dubbed *valid stop trials*. Alternatively, stop trials containing stop signals that should not be stopped to are dubbed *invalid stop trials*. The four stop tasks were presented for each factorial combination of Discriminability and SRC

condition. Each stop task contained three blocks of 120 trials each. Task order was counterbalanced across subjects.

Procedure

Subjects performed their tasks in a quiet, dimly lit room in groups with a maximum of three in one session of about three hours. Participants were instructed to respond as fast and as accurately to imperative signals as possible. For the stop tasks, again, the subjects were instructed to respond quickly and accurately to the primary task and not to delay their manual responses to increase the chances of stopping in anticipation of a stop signal to occur. Furthermore, it was explained that stop-signal onset would vary across trials, and that some stop signals will occur early so that they will always be able to stop and some will occur late so that they will rarely be able to stop.

Half of the subjects started the experimental session with the standard AFM tasks; the other half completed the stopping tasks first. The standard AFM tasks were administered in eight blocks; two blocks of 100 trials each for each possible combination of Discriminability (high, less) and SRC (compatible, incompatible). Task order was counterbalanced across subjects and the first block of every task was for practice only. The mapping of the primary-choice task in the stop tasks (which hand was coupled with which eyebrows) was counterbalanced across subjects, and did not change during the session. The primary-choice task was practiced in a separate training block of 100 trials without stop signals before stop tasks were administered.

The four stop tasks were presented for each Discriminability and SRC condition containing four blocks of 120 trials each. Order was counterbalanced across subjects. Again, the first block was for practice only, and was not analyzed further. Performance feedback was provided after each block. Trial blocks were separated by short intermissions and a longer rest separated the different tasks during which participants could move around freely. The first four trials of every task block were marked as warm-up trials and excluded from analysis.

5.2.2 Results and discussion

Mean RTs were computed for correct trials after removal of outliers (i.e., RT > $M \pm 2.5$ *SD*). Two subjects did not complete all of the standard AFM conditions and were therefore excluded from subsequent analysis.

Standard AFM tasks

Mean RTs of correct trials and choice error percentages were calculated per subject and analyzed in a 2 x 2-factorial design with Discriminability (high vs. less) and SRC (compatible vs. incompatible). The results obtained in the standard AFM tasks are listed in Table 5.2 and Figure 5.2.

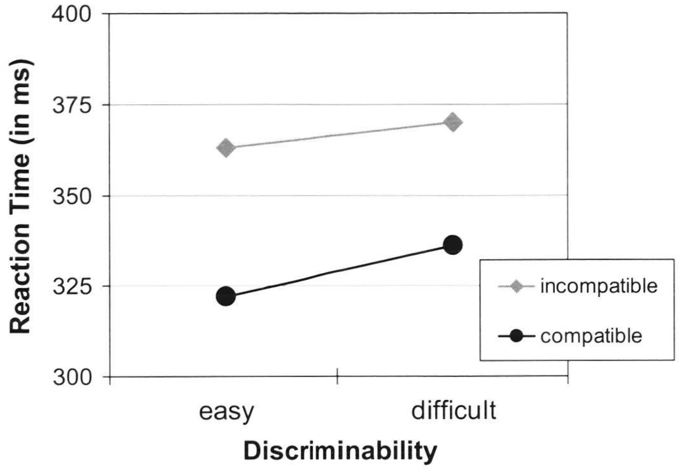


Figure 5.2: Reaction times obtained in the standard AFM tasks.

Table 5.2: Mean reaction times (RT in ms), mean error percentages, and standard deviations (in parentheses) per discriminability (high vs. less) and SRC (compatible vs. incompatible), and mean effect size (incompatible RT minus compatible RT) in the standard AFM tasks.

	S-R Compatibility				
	Compatible		Incompatible		Effect
Discriminability	RT	Error (%)	RT	Error (%)	size
high	322 (42)	2.7 (2.3)	363 (53)	4.1 (3.4)	41
less	336 (44)	3.0 (1.6)	370 (64)	4.8 (3.3)	34

First, SRC had a highly significant main effect on RT, F (1, 21) = 44.5, p < .001, and on choice errors, F (1, 21) = 6.7, p = .02, with faster and more correct responses on trials with compatible (M = 329 ms) than with incompatible mapping (M = 366 ms). Second, Discriminability had a significant main effect on RT, F (1, 21) = 4.9, p < .05, but not on choice errors, F (1, 21) = 1.0, p = .33. On average, RTs from trials with the easy-to-discriminate pupil positions (M = 342 ms) were 11 ms faster than RTs from the task blocks with hard-to-discriminate pupil positions (M = 353 ms). Finally, Discriminability and SRC did not interact significantly for RT (F < 1, p = .40) and errors, (F < 1). As predicted, the present findings showed an additive pattern of effects of Discriminability and SRC on mean RT, suggesting that the present design successfully manipulated two independent stages of information processing.

Selective stop tasks

Go trials. RT and error percentages on go-signal trials in the stopping tasks are listed in Table 5.3. RTs to the primary-task stimulus did not vary significantly between stop tasks, $F < 1$. Neither did errors, $F < 1$. This finding adds to the independence assumption of the horse-race model, as performance on the go task is not affected by selective stop instructions (compatible vs. incompatible stopping) or stop-signal discriminability (high vs. less).

Table 5.3: Mean reaction times (RT in ms), mean error percentages, and standard deviations (in parentheses) on go-signal trials per selective stopping task by stop SRC (compatible vs. incompatible) and stop-signal discriminability (high vs. less), and mean effect size (incompatible RT minus compatible RT).

	Stop-signal response compatibility			
	Compatible		Incompatible	
Stop-signal discriminability	RT	Error (%)	RT	Error (%)
high	404 (46)	2.8 (2.6)	401 (46)	3.6 (3.6)
less	407 (53)	3.6 (4.3)	397 (41)	3.0 (2.1)

Invalid stop trials. Stop signals appearing opposite to the correct response hand in compatible stopping tasks, and stop signals appearing on the same side as the correct response hand in incompatible stopping tasks are invalid stop signals and primary-task responses should not be inhibited. The ANOVA on RTs on these invalid stop trials yielded no significant main effect of Stop task ($F < 1$). As Table 5.4 shows, responses to invalid stop signals (526 ms) were on average slower than responses to go trials (402 ms), $F(1, 23) = 263.2, p < .001$.

Table 5.4: Mean reaction times (in ms), error percentages, and standard deviations (in parentheses) on invalid stop trials per selective stopping task by stop SRC (compatible vs. incompatible) and stop-signal discriminability (high vs. less), and mean effect size (incompatible RT minus compatible RT).

	Stop-signal response compatibility				
	Compatible		Incompatible		
Stop-signal discriminability	Invalid RT	Error (%)	Invalid RT	Error (%)	Effect size
high	397 (50)	8.2 (8.7)	420 (65)	4.1 (5.2)	3
less	406 (58)	8.2 (7.7)	446 (56)	5.4 (5.1)	40

Valid stop trials. Response probability was somewhat higher than the anticipated 50%. The probabilities of responding given a valid stop signal in the compatible stop and incompatible stop tasks were .55, and .58 respectively. These proportions of failed inhibits did not differ significantly between stop tasks, F (3, 21) = 2.5, p = .09. Mean stop-signal delay in the compatible stop task (160) was longer than incompatible stop delays (133), F (3, 23) = 6.9, p = .02.

Table 5.5: Mean proportions of failed inhibits (FI, in %), mean stop-signal delays (SS-delay), signal-respond reaction times (SRRT), stop-signal reaction times (SSRT), and standard deviations (in parentheses) for each stop task by stop SRC (compatible vs. incompatible) and stop-signal discriminability (high vs. less).

	Stop signal - response compatibility							
	Compatible				Incompatible			
Stop-signal discrimin-ability	FI (%)	SS-delay	SRRT	SSRT	FI (%)	SS-delay	SRRT	SSRT
high	55 (8)	158 (61)	397 (50)	252 (56)	58 (8)	142 (60)	420 (66)	270 (63)
less	55 (6)	162 (65)	406 (58)	248 (41)	58 (9)	124 (46)	446 (56)	282 (68)

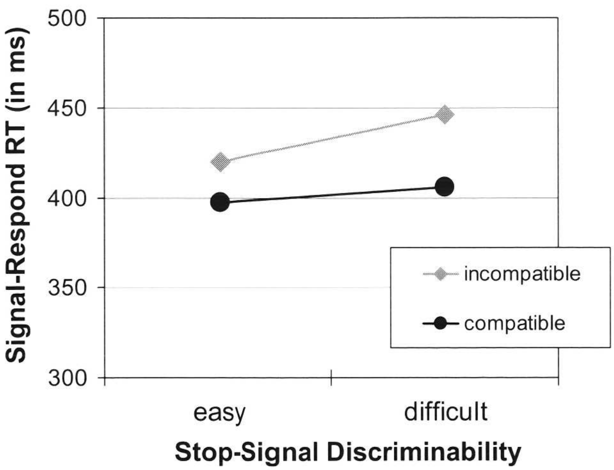


Figure 5.3: Reaction times on signal-respond trials.

Interestingly, analysis of RTs on signal-respond trials (i.e., go responses on stop trials that escaped inhibition) revealed a typical AFM-like pattern, with a main effect (32 ms) of SRC, F $(1, 23) = 18.7, p < .001$, and a main effect (17 ms) of Discriminability, $F(3, 23) = 5.8, p = .03$. These effects turned out to be additive, $F(1, 23) = 1.7, p = .20$. This pattern suggests that signal-respond processes consisted of at least two independent stages, stimulus analysis and response choice. Contrary to the prediction of the hose-race model, responses that escaped inhibition on stop trials (signal-respond RT 417 ms) were significantly *slower* than responses on go trials (402 ms), $F(1, 23) = 8.3, p < .01$.

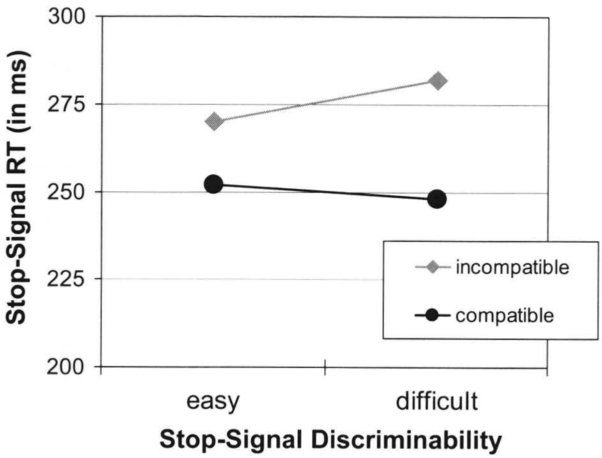


Figure 5.4: Stop-signal reaction times.

Finally, and most importantly, a set of ANOVA analyses performed on selective stop latencies revealed a significant effect of SRC, $F(1, 23) = 8.0, p = .01$. Stop latencies to incompatible stop signals (i.e., when subjects were instructed to inhibit to stop signals appearing contralateral to the response hand) were longer (276 ms), compared to stop latencies associated with compatible stop signals (250 ms). Stop-signal discriminability did not affect stop latency (SSRT high discriminability = 261 ms vs. SSRT less discriminability = 265 ms, $F < 1$). A significant interaction between stop SRC and Discriminability on stop latency was absent, F $(1, 23) = 1.7, p = .20$.

It could be argued that the strategy of postponing the inhibitory response could bias the estimation of stop latencies because this procedure involves cutting in the distribution of no-signal RTs. Application of this procedure would systematically underestimate SSRT. Therefore, an alternative procedure was carried out, to compensate for stop signal interference on primary- task processing, basing the estimation of SSRT not on no-signal trials but on RTs obtained on invalid signal trials.[2] The pattern of these adjusted SSRTs is consistent with the

[2] A similar procedure for estimating selective stopping latencies associated with responses executed by a critical hand in a selective stopping paradigm has been reported by De Jong et al., 1995, Exp. 2.

original SSRTs obtained in this experiment; Incompatible stopping tends to be slower than compatible stopping, respectively, 428 ms vs. 384 ms, F (1, 23) = 3.7, p = .07 but stop-signal discriminability did not affect adjusted stopping latency, (F < 1). In conclusion, despite of subjects delaying their inhibitory response, the SRC pattern observed for stop latencies in the present study is likely to be consistent.

Although our manipulation of signal discriminability yielded the anticipated RT pattern in the standard AFM tasks, it did not systematically affect the latency of the stop processes in the selective stop tasks. To explore these disparate findings further, we focused on possible dissimilar effects of discriminability across subjects. Therefore, a median split was performed, ranking subjects according to the magnitude of the discriminability effect in the standard AFM tasks. A post-hoc ANOVA was conducted with an additional between-subject variable of subgroup (large effect of discriminability vs. small effect of discriminability on the standard AFM tasks). A significant three-way interaction indicated that SRC and Discriminability effects on RT in the standard AFM tasks differed between Subgroups, F (1, 21) = 5.6, p = .03. Returning to the stopping tasks, a subsequent ANOVA conducted on the Subgroup that exhibited a relative large discriminability effect on RT revealed a significant main effect of discriminability on SSRT F (1, 11) 18.0, p < .001, see Figure 5.5. Unfortunately, within this subgroup, the main effect of stop SRC just failed to reach significance, F (1, 11) = 3.4, p < .10. Finally, Stop-Signal discriminability and stop SRC did not interact significantly (F < 1).

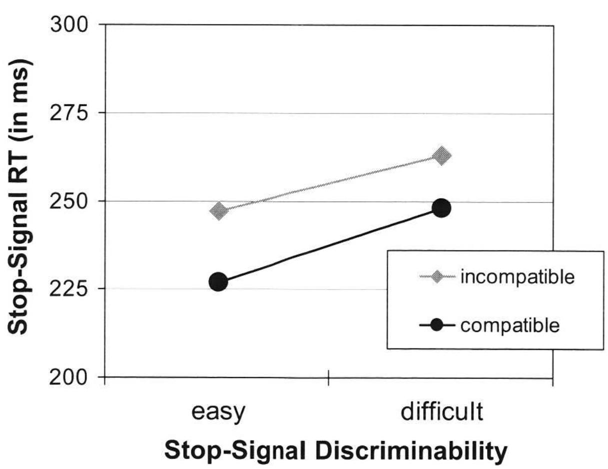


Figure 5.5: Stop-signal reaction times including a subset of subjects with a relatively large effect of signal discriminability in the standard AFM tasks.

Summarizing, the manipulation of stop SRC had significant mains effect on the go process and the stopping process. Compatible responses were executed faster (RT) and inhibited at faster rate (SSRT) than incompatible responses. The experimental manipulation of discriminability yielded the anticipated effects on RT in the standard AFM tasks – responses to easy-to-discriminate stimuli were faster than responses on difficult-to-discriminate trials. However, when employed in the stop-signal task, stop-signal discriminability failed to systematically affect selective stopping latency; stopping latencies to easy and hard to discriminate stop signals were of comparable magnitude. However, post-hoc analysis that included those subjects that exhibited a relatively large discriminability effect on RT yielded the anticipated effects of stop-signal discriminability on SSRT. Therefore, Experiment II was conducted using harder-to-discriminate stop signals than the ones used in Experiment I.

5.3 EXPERIMENT II

5.3.1 Method

Subjects

Fifteen undergraduate students (10 females, mean age = 21.2 years) participated to fulfill course requirements. All reported to be healthy and had normal or corrected-to-normal vision. No subject took part in more than one experiment reported in this study.

Apparatus and signals

The apparatus was identical to that in Experiment I. The size of schematic face employed in Experiment II was reduced by 50%. The relative distance of the pupils (diameter 2 mm) serving as imperative signals in the standard AFM tasks and as stopping signals in the stop tasks was reduced also and could appear either 1 mm to the left or right with respect to the center of the eyes (hard signal discriminability) or at a distance of 4 mm from the center, that is in the outer left or right canti of the eyes (easy signal discriminability).

Tasks, design, and procedure

Design, procedure, and instructions of the standard AFM tasks as well as stopping tasks in Experiment II were similar to Experiment I.

5.3.2 Results and discussion

Mean individual RTs were computed for correct trials only and outliers (i.e., RT > $M \pm 2.5$ *SD*) were removed.

Standard AFM tasks

Go trials without a response were less than .2%. Mean RTs of correct trials and choice error percentages were calculated per subject, for each factorial combination of Discriminability and SRC levels. RTs and square roots of choice error percentages were analyzed in a 2 x 2-factorial design with Discriminability (high vs. less) and SRC (compatible vs. incompatible) as within-subjects factors. The results obtained in the standard AFM tasks are listed in Table 5.6, and a plot of the RT data is presented in Figure 5.6.

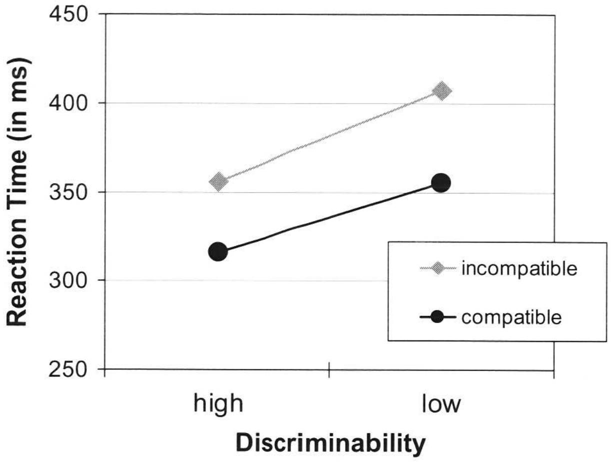


Figure 5.6: Reaction times in the standard AFM task.

First, Discriminability had a highly significant main effect on RT, $F\ (1, 14) = 75.31, p < .001$, and choice errors, $F\ (1, 14) = 8.58, p = .011$. On average, RTs from trials with the easy-to-discriminate pupil positions ($M = 336$ ms) were 45 ms faster than RTs from the task blocks with harder-to-discriminate pupil positions ($M = 381$ ms). This 45 ms effect is more pronounced than the 11 ms difference between discriminability conditions reported in Experiment I. In addition, the effect of Signal discriminability on errors turned out to be significant in Experiment II, whereas was not significant in Experiment I. Taken together, the effects of Signal discriminability on RT as well as on errors indicates that the signal positions of Experiment II were indeed harder to discriminate than the ones employed in Experiment I, as anticipated. Second, compatibility of the location of the respond signal and the location of the response button had a significant main effect on RT, $F\ (1, 14) = 55.66, p < .001$, and on choice errors, $F\ (1, 14) = 12.43, p = .003$, reflecting faster responses on trials with compatible ($M =$ 336 ms) than with incompatible mapping ($M = 381$ ms). Third, Discriminability and SRC did not interact significantly in the RT, $F\ (1, 14) = 3.81, p > .05$, or errors, $F < 1$.

Table 5.6: Mean reaction times (RT in ms), mean error percentages, and standard deviations (in parentheses) per Discriminability (high vs. less) and SRC (compatible vs. incompatible), and mean effect size (incompatible RT minus compatible RT) in the standard AFM tasks.

	S-R Compatibility				
	Compatible		Incompatible		Effect
Discriminability	RT	Error (%)	RT	Error (%)	size
high	316 (24)	3.9 (2.9)	356 (31)	5.2 (2.9)	40
less	355 (25)	5.7 (3.6)	407 (43)	8.3 (4.9)	52

Selective stop tasks

Go trials. RTs and error percentages on go-signal trials on the stopping tasks are listed in Table 5.7. RTs to the primary-task eyebrows did not vary significantly between stop tasks, F (3, 12) = .76, p = .54. Go RTs did not yield significant main effects of SRC, F (1, 14) = 2.51, p = .14, or Discriminability, $F < 1$, nor a significant interaction, F (1, 14) = .87, p = .37. Error percentages on go trials did not differ either between selective stop tasks, F (3, 12) = 1.40, p = .29 (absent main effects of SRC, $F < 1$, Discriminability, F (1, 14) = 1.50, p = .24, a significant interaction between these effects was also absent, F (1, 14) = 1.99, p = .18).

Table 5.7: Mean reaction times (RT in ms), mean error percentages, and standard deviations (in parentheses) on go-signal trials per selective stopping task by stop SRC (compatible vs. incompatible stopping) and stop-signal Discriminability (high vs. less), and mean effect size (incompatible RT minus compatible RT).

	Stop-Signal Response Compatibility				
Stop-Signal	Compatible		Incompatible		Effect
Discriminability	RT	Error (%)	RT	Error (%)	size
high	416 (45)	3.0 (2.0)	426 (35)	3.5 (2.1)	10
less	416 (47)	3.7 (1.9)	420 (46)	3.5 (3.1)	4

Invalid stop trials. Responses on trials with an invalid stop signal should not be inhibited. The ANOVA on RTs on invalid stop trials yielded no significant main effect of Stop task ($F < 1$). As Table 5.8 shows, responses to invalid stop signals (529 ms) were on average slower than responses to go trials (420 ms), F (1, 14) = 99.3, $p < .001$.

Table 5.8: Mean reaction times (in ms), error percentages, and standard deviations (in parentheses) on invalid stop trials per selective stopping task by stop SRC (compatible vs. incompatible stopping) and stop-signal discriminability (high vs. less), and mean effect size (incompatible RT minus compatible RT).

	Stop-signal response compatibility				
	Compatible		Incompatible		
Stop-signal discriminability	Invalid RT	Error (%)	Invalid RT	Error (%)	Effect size
high	525 (56)	7.7 (5.4)	532 (47)	2.8 (4.8)	6
less	526 (46)	7.3 (4.3)	534 (62)	3.3 (4.0)	8

Valid stop trials. Results obtained on valid stop trials are presented in Table 5.9. Response probability was somewhat higher than the anticipated 50%. The probabilities of responding given a valid stop signal in the compatible stopping tasks were .57 (high stop-signal discriminability and .59 (less stop-signal discriminability), and .56 (high stop-signal discriminability and .59 (less stop-signal discriminability) in the incompatible stopping tasks. The proportions of failed inhibits did not differ significantly between stop tasks, F (3, 12) = 1.8, p = .20. Mean stop-signal delay did not vary with Stop task, F (3, 12) = 1.1, p = .37.

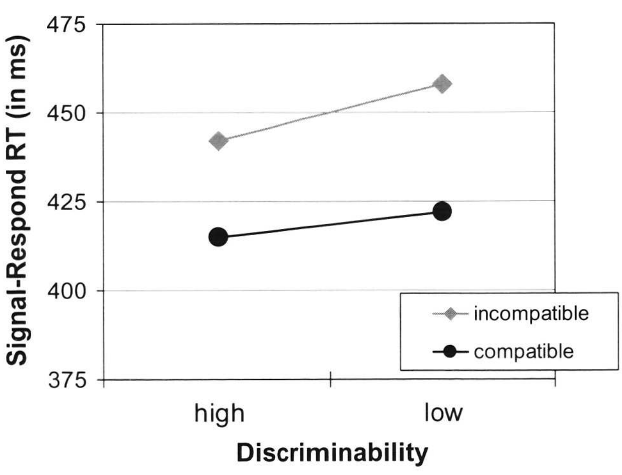


Figure 5.7: Reaction times on signal-respond trials.

Table 5.9: Mean proportions of failed inhibits (FI, in %), mean stop-signal delays (SS-delay), signal-respond reaction times (SRRT), stop-signal reaction times (SSRT), and standard deviations (in parentheses) for each stop task by stop SRC (compatible vs. incompatible) and stop-signal discriminability (high vs. less).

	Stop signal - response compatibility							
	Compatible				Incompatible			
Stop-signal discriminability	FI (%)	SS-delay	SRRT	SSRT	FI (%)	SS-delay	SRRT	SSRT
high	57 (9)	138 (62)	415 (51)	283 (54)	56 (10)	145 (49)	442 (50)	288 (55)
less	59 (8)	144 (68)	422 (50)	282 (61)	59 (11)	132 (47)	458 (64)	301 (47)

Contrary to predictions of the horse-race model, responses that escaped inhibition in stop trials (signal-respond RT 435 ms) did *not* differ significantly from responses on go trials (420 ms), F (1, 14) = 3.9, p > .05. ANOVA on signal-respond RTs yielded a significant effect SRC, F (1, 14) = 11.7, p > .01, but the effect of Discriminability was not significant, F < 1.

Finally, and most importantly, selective stopping latencies did not differ between selective stopping tasks, F (3, 12) = 1.9, p = .19 (see Figure 5.8). The main effects of the factors stop SRC and Discriminability did not reach significance, F (1, 14) = 1.9, p = .19 and F (1, 14) = 1.2, p = .30, respectively, nor did the interaction, F (1, 14) = 1.1, p = .30.

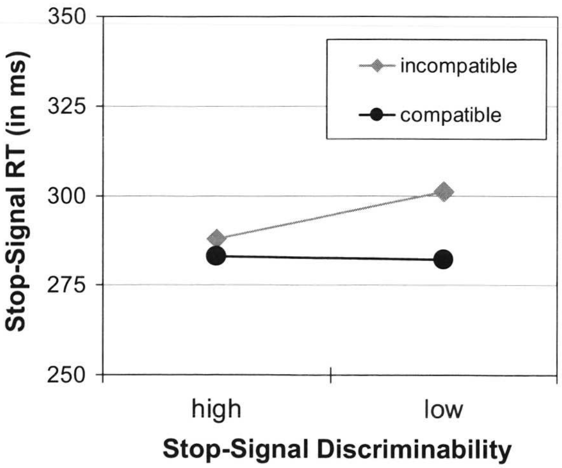


Figure 5.8: Stop-signal reaction times.

5.4 General discussion

The present experiments were designed to independently manipulate two stages of information processing of go signals in a standard choice task, and of stop signals in a stop-signal task. Varying the similarity between two imperative signals manipulated the factor signal discriminability. In turn, two levels of signal-response compatibility (SRC) were induced by varying the degree of natural overlap between signal and response. The standard AFM experiments (Experiment I as well as Experiment II) showed the anticipated RT pattern. First, a main effect of signal discriminability on choice RT was obtained – responses to harder discriminable stimuli were slower than to easy discriminable signals. Second, a main effect of SRC indicated that incompatible responses were completed slower than compatible responses. Importantly, the main effects of signal discriminability and SRC proved to be additive, which suggests that the two variables did indeed affect separate stages of go-signal processing independently. The consistent RT pattern observed in the present standard AFM tasks are in line with the results typically reported in the AFM literature (Blackman, 1980; Hasbroucq, Guiard, & Kornblum, 1989; McCarthy & Donchin, 1981; Mulder, Gloerich, Brookhuis, van Dellen, & Mulder, 1984; Schwartz, Pomerantz, & Egeth, 1977; Shulman & McConkie, 1973; Shum, McFarland, & Bain, 1994; Shum, McFarland, Bain, & Humphreys, 1990; Sommer, Leuthold, & Hermanutz, 1993; Stoffels, 1988). Signal discriminability most likely affected early, possibly perceptual, stages of signal processing. SRC is believed to have its impact mainly in the later motor stages of information processing (Sternberg, 1969; see reviews in Sanders, 1990; 1998).

To establish whether the AFM could be used as a tool to infer stages of stop-signal processing we used go signals of the standard AFM tasks served as a stop signal in the stopping tasks. Instead of triggering a go response, the signals to set off the inhibitory response. Hence we predicted the factors (stop-)signal discriminability and (stop-)signal / (go-)response compatibility to produce additive effects on stopping latency, according to the pattern observed in the standard AFM tasks.

The present selective stopping tasks required subjects to discriminate between valid and invalid stop signals based on the spatial relation between the location of the response hand indicated by the go stimulus and stop-signal location. The relation between stop-signal location and go-response hand could either be compatible or incompatible. Compatible stopping conditions required subjects to stop their primary-task response only if the location of the stop signal was spatially compatible with the correct response hand, whereas incompatible stopping instructions required subjects to inhibit to stopping signals that are located opposite to the planned response. These instances indicated *valid stop signals*. Subjects were instructed to trigger their inhibitory response only upon the presentation of a valid stop signal, as opposed to invalid stop signals that did not require response inhibition. The present stopping tasks differs in several respects from the selective stopping tasks that have been reported previously. Compared to other selective stop tasks reported in the literature (e.g., Bedard et al., 2002; De Jong et al., 1995; Van den Wildenberg & van der Molen, 2003a) the current setup yielded a more demanding inhibitory task load, basing the decision to invoke the stopping response on the spatial relation between stop-signal location and planned response hand. This inhibition task differs from the instruction to stop any go response at hand upon the presentation of one out of two possible stop signals (e.g., "stop your button-press response after hearing a high-

pitched tone, but continue to respond after the presentation of a low-pitched tone") (Bedard et al., 2002; Riegler, 1986). The present stopping instruction are also different from selective stopping studies that assigned one critical response out of two go responses to be inhibited upon a stop signal (e.g., "stop your right-hand response to the stopping tone, but not your left-hand response") (De Jong et al., 1995).

Although the current stopping instructions were quite demanding, subjects were able to stop their primary-task response in a selective manner, as indicated by the low inhibition rates to invalid stop signals (see also Bedard et al., 2002). The results obtained in Experiment I indicate that selective stopping latencies to incompatible stop signals were about 11 ms slower compared to stopping latencies associated with compatible stop signals. This difference is small, yet significant and the effect is of similar magnitude and direction as the significant 10 ms difference between compatible and incompatible stopping reported by Van den Wildenberg and van der Molen, (2003a). Thus, manipulations of SRC had similar effects on go-RT as well as on SSRT, which can be interpreted in terms of the vast literature suggesting that spatial SRC alters the speed of response selection (for a review see Sanders, 1998).

Before interpreting stopping latencies, the current stopping data will first be discussed in terms of the horse-race model of stopping control. Although the inhibition conditions in the four stopping tasks varied systematically according to the factorial combination of stop-signal discriminability and stop-signal / responses compatibility, the go task was held constant over stop tasks. It is important to note that the go-responses on the primary tasks did not vary between stopping conditions. This observation indicates that variations in the demand of stop-signal processing and stopping instructions did not systematically affect primary-task processing. This is in line with the assumption of independence formulated by the horse-race model (Logan, 1994; Logan & Cowan, 1984).

The horse-race model further predicts that RTs from trials in which subjects were presented with a stop signal and failed to inhibit (signal-respond RTs), on average, should be faster than no-signal RTs. Contrary to this prediction, it was observed that signal-respond RT did *not* differ significantly from responses on go trials (Experiment II) and that signal-respond RTs were even significantly *slower* than responses on go trials (Experiment I). The present data could be taken to suggest that subjects deliberately delayed their inhibitory response to the point at which they were certain that the signal presented was a valid stop signal. This strategy kept them from eliciting high commission rates to valid stop signals. Signal-respond RTs being slower than no-signal RTs indicate that discriminating between stop-signals interfered with primary-task processing and therefore, the left part of the no-signal distribution containing fast RTs might not be representative of the population signal-respond RTs. Thus, the strategy of postponing the inhibitory response could bias the estimation of stopping latencies. However, estimation of SSRT using an alternative procedure that accounts for this strategy yielded similar effects of discriminability and SRC.

Thus, it seems that the current design successfully manipulated later stages, probably affecting the motor end of stop-signal processing. Unfortunately, we were less successful in obtaining significant effects in earlier, perceptual stages of stop-signal processing. Although the discriminability manipulations resulted in the anticipated RT pattern in the standard AFM tasks, varying stop-signal discriminability did not systematically affect selective stopping speed – selective stopping to easy to discriminate stop signals was as fast as stopping to harder to discriminate stop signals. Based on the obtained SSRT pattern it was inferred that the current levels of discrimination did not effectively affect stopping speed, possibly because harder

to discriminate stopping signals were not that hard to discriminate. This conjecture was confirmed by follow-up analysis on a subset of subjects selected on the basis of a relatively large effect of signal discriminability in the standard AFM tasks. SSRTs obtained from this subset showed the anticipated effects of stop-signal discriminability and compatible stopping tended to be faster than incompatible stopping. Moreover, these main effects proved to be additive with respect to SSRT. This pattern indicated that, at least in a subset of participants, signal discriminability and SRC affected two stages of stop-signal processing independently.

Experiment II was designed to replicate the promising findings of Experiment I; Experiment II included a level of harder-to-discriminate signals than in Experiment I by reducing the distance between the positions of the stop signal relative to the midline, making it harder to discriminate. Again, the anticipated effects were found on go-RT, but unfortunately, we did not obtain significant effects of signal discriminability nor SRC on selective stopping latency.

In conclusion, the present experiments combined the additive factors method and the stop-signal paradigm to examine stages of stop-signal information processing. The current pattern of findings indicate that the logic of the AFM on go-signal processing does not fully extend to stop-signal processing, at least with the stop signals used in the present study. This failure should not be taken to imply that stop-signal processing does not comprise identifiable processing stages. But instead that careful implementation of factorial levels might elucidate stages of stopping. Manipulation of experimental variables other than the ones used in the present study should reveal whether the stop process consists of similar processing stages as the reaction process.