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## Stopping responses in the Simon paradigm : Examining the nature of simple and selective response inhibition

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### Abstract

The present study is concerned with the nature of stop processes involved in stop-signal inhibition. We combined the stop-signal paradigm and the Simon paradigm that has proven to be useful in investigating the nature of go processes. Simon-like factorial manipulations were applied to stop signals in a simple stop task and in two selective stop tasks. We observed a zero congruency effect with less discriminable stop signals, and a non-zero congruency effect with highly discriminable stop signals and on RT as well as on SSRT. The results confirm our conjecture that go processes and stop processes triggered by Simon signals are comparable. The present results indicate that stop-signal processing can be described by a dual-process architecture that incorporates a direct location-based route and a controlled identification-based route for response inhibition. This finding may provide a handle for future studies aimed at providing a deeper understanding of the nature of stop-signal inhibition.

### 6.1 Introduction

The present study is concerned with the active type of response inhibition that is manifested in several experimental procedures ranging from relatively simple tasks, such as the go/nogo task (Donders, 1868/1969) and the antisaccade task (Hallet, 1978), to more demanding tasks, such as the Stroop test (Stroop, 1935) and the Simon task (Simon & Rudell, 1967), to more complex problem-solving tasks, such as Wisconsin Card Sorting Task (WCST; Grant & Berg, 1948). These paradigms share the requirement that a prepotent response must be suppressed. Most procedures are limited to the extent that the efficiency of response suppression processes must be inferred from either the absence of the prepotent response (e.g., the go/nogo task) or the slowing of the correct response (e.g., the WCST or conflict tasks such as the Stroop). Non-invasive electrophysiological measurements may further elucidate the efficiency of inhibitory processes (e.g., event-related brain potentials related to response suppression in nogo trials), but the specificity of some of these indices to the involvement of inhibitory processes has been challenged (Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, in press). Two paradigmatic approaches (and, particularly, the methodological procedures associated to these approaches) have been suggested to provide more explicit tools in studying the efficiency of inhibitory control over response activations, the stop-signal paradigm developed by Vince (1948; see also Lappin & Eriksen, 1966) and formalized by Logan and Cowan (1984), and the delta-plot technique for distributional analysis of conflict-task performance developed by Ridderinkhof (2002a).

### 6.1.1 *The stop-signal paradigm*

In the stop-signal paradigm, subjects typically perform a standard two-choice task but, infrequently and unpredictably, a stop-signal may be presented which countermands the planned response to the go signal. According to the underlying theory (Logan, 1994; Logan & Cowan, 1984) the subject's ability to inhibit the overt response depends on the outcome of a race between two independent processes, the go process and the stop process. If the go process wins the race, the response will be executed. By contrast, if the stop process wins the race, the planned go response will not occur. Thus, the ability to inhibit depends on the latency of the stopping response to the stop signal (i.e., stop-signal reaction time or SSRT). The clear advantage of the stop-signal paradigm over other procedures is that it provides a reasonably accurate approximation of the efficiency of the internal act of control involved in stopping, even though successful inhibition does not produce overt behavior. Conceptually, the type of inhibition manifested in the stop-signal paradigm is one of several intentional acts of control that is required in many real life situations (e.g., stopping for a red traffic light) and is exercised by a higher-order executive system (e.g., Norman & Shallice, 1986).

### 6.1.2 *A selective review of stop-signal studies*

In using the stop-signal paradigm to investigate the nature of response inhibition, several researchers have combined the requirement to interrupt on-going actions in response to stop signals with variations in the demand on inhibitory control exerted by primary-task processing. For example, stopping latencies have been reported to be comparable for spatially compatible and incompatible responses (Logan, 1981; Logan & Irwin, 2000; Van den Wildenberg & van der Molen, 2003a). 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 introduced stop-signals in an Eriksen flanker task requiring the inhibition of responses to target stimuli flanked by distracters assigned to the same or opposite response (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Ridderinkhof, Band, & Logan, 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).

Van den Wildenberg, van der Molen, and Logan (2002) adopted a similar strategy and combined primary-task requirements aimed to reduce response readiness with stop-signal inhibition. Subjects performed a primary task that required 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. This setup induced periods of tonic inhibition (i.e., episodes of reduced response readiness). The tonic inhibition episodes were contrasted with control episodes during which subjects were ready to execute a speeded choice reaction (i.e., trial sequences consisting of go trials only). During both episodes, a visual stop signal could occasionally and unpredictably follow the go-signal onset, instructing subjects to withhold their

response to the go signal. Responding on go trials was delayed during tonic inhibition episodes relative to control episodes suggesting that cuing reduced the readiness to respond. Most importantly, stopping was delayed during tonic inhibition episodes. 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). According to this model, reduced readiness is associated with more forceful responses because when in an unprepared state, a larger increment is needed to cross the action threshold associated with the generation of a response. A follow-up study confirmed the conjecture that more forceful responses take longer to inhibit (Van den Wildenberg, van Boxtel, & van der Molen, 2003).

In summary, the overall data pattern that emerges from studies that introduced stopping in a choice task that draws upon another form of inhibitory control suggest that relatively slower primary-task responses due to inhibitory demands are associated with delayed stop latencies (Kramer et al., 1994; Ridderinkhof et al., 1999; Van den Wildenberg, van Boxtel, & van der Molen, 2003; Van den Wildenberg, van der Molen, & Logan, 2002).

### 6.1.3 *Extending the simple stop task: The selective stop response*

In the stop tasks reviewed in the previous section, the stop signal instructs the subject to inhibit prepotent responses in an all-or-none manner. Over the years, the standard stop-signal paradigm has been extended to cover selective stopping as a more subtle manifestation of inhibitory control than the simple stop response. For example, the stop process has been made more complex at the perceptual end of stop-signal processing by requiring discrimination between two or more stop signals. Subjects could be instructed to inhibit the planned response to one stop signal (e.g., the high-pitched tone) but not to the other (e.g., the low-pitched) tone (Riegler, 1986, cited in Logan, 1994). Typically, selective stop latencies are substantially longer than simple non-selective stop latencies. Bedard et al. (2002) suggested that non-selective (simple) stopping parallels the simple or Donders A response. Likewise, selective ('to stop or not to stop') stopping corresponds to a classic Donders' C response (go vs. nogo, see also Logan, 1994).

Other investigators of selective stopping have focused on the motor end of the stop process by instructing subjects to stop just one critical response (e.g., their right-hand response) to the stop signal but not the other (e.g., left-hand) response. Logan, Kantowitz, and Riegler (cited in Logan, 1994) used this type of selective stop task. Again, selective stopping was accompanied by longer stop latencies, and the latencies increased with the number of alternative go responses. Interestingly, simple SSRTs did not vary much between tasks – one out of four possible go responses was inhibited as fast as one out of two possible go responses.

Recently, Van den Wildenberg and van der Molen (2003a) investigated the effects of response selection demands associated with the primary task on the speed of selective stopping. Stimulus-response (S-R) compatibility (SRC) of the primary task was manipulated block-wise. In one condition, the subjects were instructed to press a button that was indicated by the direction of an arrow (compatible S-R mapping) whereas in another condition the subject should press the respond button opposite to the direction indicated by the arrow (incompatible S-R mapping). Stop signals could appear to the left or to the right of the central arrow. Subjects should inhibit their response in a selective manner, that is, to stop only if the location of the stop signal corresponded to the hand associated with the choice task (e.g., a left

hand response should be stopped only if the stop signal was presented to the left of the go signal). Interestingly, the speed of selective inhibition was determined by the response that had to be stopped. Incompatible responses were stopped slower than compatible responses. This SRC-effect on selective stopping latencies stands in marked contrast with the null finding typically reported in simple stopping tasks (Logan, 1981; Logan & Irwin 2000; Van den Wildenberg & van der Molen, 2003a). The sensitivity of selective SSRTs to the SRC mapping in the choice task extends previous findings showing an interaction between stopping and inhibitory demands of the primary task (Kramer et al., 1994; Ridderinkhof et al., 1999). But those studies were concerned with simple inhibition only and manipulated inhibitory demands of the primary task using an Eriksen flanker paradigm. The effect of SRC on selective SSRT was explained in terms of rule interference (Van den Wildenberg & van der Molen, 2003a). On compatible stop trials, the primary-task selection rule and the inhibition-task selection rule are congruent. That is, the primary-task stimulus is translated into the activation of a response at the side indicated by the direction of the stimulus (compatible mapping) and the stop stimulus is translated into the inhibition of a response activated at the same side as the stop stimulus (compatible mapping). On incompatible trials, however, the selection rules are incongruent. On those trials, the primary-task stimulus is translated into the activation of a response at the side that is opposite to the location indicated by the direction of the go stimulus (incompatible mapping). In contrast, as on compatible stop trials, the stop stimulus is translated into the inhibition of a response activated at the same side as the stop stimulus (compatible mapping). The interference between selection rules on incompatible trials may have caused the delay in selective SSRTs.

Finally, effects of SRC manipulations of the primary-choice task on stopping latency have been reported in another selective stopping task by Van den Wildenberg & van der Molen (2003a). In one block, subjects were instructed to selectively inhibit their go response, but only to stop signals that appeared on a location that was spatially compatible with the primary-task response. Alternatively, another condition required selective stopping to incompatible stop signals appearing opposite to the location associated with the go response at hand. Again, analysis of stop latencies indicated that selective stopping to spatially incompatible stop signals was slower than stopping to spatially compatible stop signals.

The present study was conducted to further explore the effects of SRC on simple and selective inhibitory motor control. We crossed the stop paradigm with the Simon task derived from the conflict paradigm. The Simon task involves a special case of SRC effects on RT and has proven to be useful in investigating the nature of go processes (see Kornblum, 1994; Simon 1990 for reviews). The next section provides a brief overview of results obtained in Simon studies and the dual-process model used to explain these findings.

#### *6.1.4 The conflict paradigm and the dual-process model*

The spatial relationship between the stimulus and the response affects task performance. Choice reactions can be carried out faster when the response corresponds spatially to the stimulus, even when the location of the stimulus is irrelevant to the task at hand. For example, when subjects are instructed to press a left or right key depending on the color of an imperative signal that is presented either to the left or to the right of a central fixation point, reaction times are generally shorter for ipsilateral (congruent) than for contralateral (incongruent)

signal-respond relations (Craft & Simon, 1970). This special case of compatibility effect is known as the *Simon effect* (Hedge & Marsh, 1975). In examining the mechanisms underlying interference effects in conflict tasks like the Simon task, many authors have reported evidence in support of a dual-route architecture of response activation (e.g., De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Hommel, 1993; Kornblum et al., 1990; Ridderinkhof, van der Molen, & Bashore, 1995; Stoffels, 1996). A schematic representation of this type of model is depicted in Figure 6.1. Most significant, the controlled process of stimulus-response (S-R) translation (cf. Sanders, 1980; Welford, 1968) is by-passed by a direct activation route (Hommel, 1993; Ridderinkhof et al., 1995); the two routes converge at the level of response activation processes. If stimuli contain both task-relevant and to-be-ignored attributes, such as in Stroop or Simon tasks, only the task-relevant attribute will activate a response along the deliberate route, but all attributes may influence the response system via the direct-activation route. Target and distracter stimulus attributes may activate the same response (in congruent stimuli; CG) or opposite responses (in incongruent stimuli, IG).

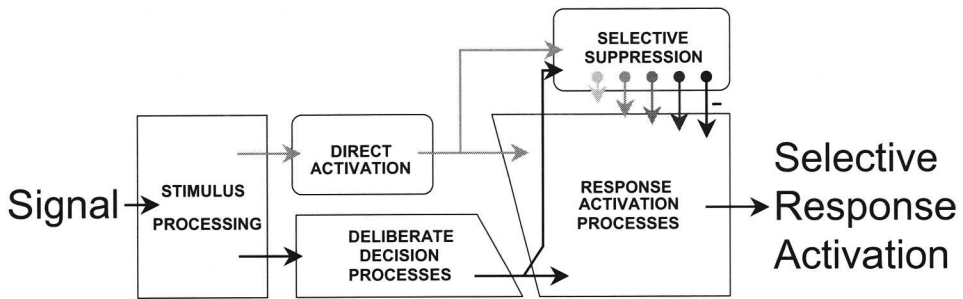


Figure 6.1: Elementary architecture of the dual-process model.

According to the activation-suppression hypothesis (Ridderinkhof, 2002a), direct activation resulting from irrelevant stimulus features is selectively suppressed, and this selective suppression takes some time to build up (see also Eimer, 1999). In Figure 6.1, the schematic representation of the dual-process model incorporates these selective suppression processes.<sup>1</sup> Like most mental processes, both the activation of responses and the selective suppression of direct activation are subject to variability. The time to encode and identify stimulus features and to select appropriate responses on the basis of target features varies from trial to trial and, as a consequence, the time course and strength of direct activation vary from trial to trial. The strength, onset time, and/or build-up rate of selective suppression of direct activation may also vary from trial to trial. In conditions where selective suppression is relatively strong (or starts early, or builds up quickly), the effects of direct activation should be shorter-lived than in conditions where selective suppression is relatively weak (or starts late, or builds up slowly); the build-up of activation for the incorrect response along the direct-activation route would be able to attain a lesser magnitude before being corrected by selective suppression processes. As

<sup>1</sup> For matters of clarity, the inhibition of task-irrelevant information is referred to as *response suppression*. The term *response inhibition* is reserved to the selective inhibition of responses in the stop-signal paradigm.

one consequence, the activation of the incorrect response along the direct-activation route will exceed the response threshold sooner when selective suppression is weak compared to strong. In other words, under a stronger inhibition regime, one may more often prevent incorrect activation from resulting in an overt response.

Thus, in going from weak to strong suppression, fewer fast errors would occur in response to IG stimuli. More important, in strong-suppression compared to weak-suppression conditions the effects of direct activation should be shorter-lived, so that activation for the *correct* response to IG stimuli should benefit (i.e., it can be initiated earlier and build up more quickly). With weak inhibition, only the slower IG responses benefit from selective suppression; with stronger inhibition, the facilitation of IG responses will be more pronounced, and faster incongruent responses will also benefit from selective suppression. Evidence for the activation-suppression hypothesis and its predictions with respect to the dynamics of direct activation and selective suppression was derived from distributional analyses of behavioral data (RT and accuracy; Ridderinkhof, 2002a; 2002b). The distribution-analytic approach allows for a careful examination of these temporal dynamics, and the delta-plot technique has been applied successfully to study effects on inhibitory control elicited by alcohol consumption (Ridderinkhof et al., 2002), speed/accuracy instruction (Band, Ridderinkhof, & van der Molen, in press), post-error adaptation (Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002), or individual differences such as those related to ADHD (Ridderinkhof, Scheres, Oosterlaan, & Sergeant, 2003).

#### 6.1.5 Combining stop and conflict paradigms

The stop-signal paradigm and the conflict paradigm provide us with useful indices (SSRT and delta plot slopes) of the efficiency of response inhibition. However, the efficiency of these processes is inferred indirectly from mathematical/statistical procedures; these procedures do not allow for a direct examination of the nature of response inhibition processes. The nature and efficiency of go processes have been studied extensively through parametric variations in factorial manipulations of the go process. Likewise, the nature of stop processes may also be studied systematically through parametric variations in factors that may influence the stop process. This was the purpose of the present study. Parametric variations were aimed at manipulating the efficiency of various components of the stop process, much as factorial manipulations have been used to study the efficiency of the go process.

In particular, in the present study we test the assumption that stop processes are 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 require perceptual discrimination, translation into an appropriate action (i.e., inhibition of ongoing responses), and then the programming and unfolding of that inhibitory action. In the go task, activation and suppression result in execution and inhibition of responses, respectively. In the stop task, by contrast, we construe activation of stop processes to result in response *inhibition* while suppression of this activation is construed to result in response *disinhibition* (which boils down to response execution). This analogy provides us with a context in which the stop process can be studied in a fashion similar to the explorations of the go process.

The conceptual framework of the dual-process model, that has been used extensively to explore activation and suppression in go processes, will be used here to study activation and suppression in stop processes as well. Activation and suppression in go processes will be verified using a stimulus-discriminability manipulation in a Simon task; activation and suppression in stop processes will be examined by using the same manipulation in the stop task. We will first elaborate on the predictions for the Simon task as derived from the dual-process model; next, we will generalize these predictions to the stop task.

### *The Simon task*

The response system receives activation from both the deliberate route and the direct route. Activation from the direct route is subsequently suppressed, but this inhibition takes some time to build up. Therefore, on occasions where processing along the deliberate route is rapid, the operation of selective suppression comes into play relatively late, resulting in a relatively large congruency effect on RT. If the deliberate route is less rapid, then selective suppression operates more timely, such that the initial direct activation is selectively suppressed (sometimes so strongly that the net result is relative facilitation of the opposite response, as expressed in a reversed congruency effect; see Eimer, 1999). If the deliberate route is quite slow, then selective suppression operates relatively early, such that all initial activations have decayed by the time the deliberate route is finished (resulting in a zero congruency effect on RT). Thus, with highly discriminable signals the deliberate route can operate rapidly, resulting in a non-zero congruency effect (either positive or negative, depending on relative timing); with less discriminable signals the deliberate route operates more slowly, resulting in a zero congruency effect.

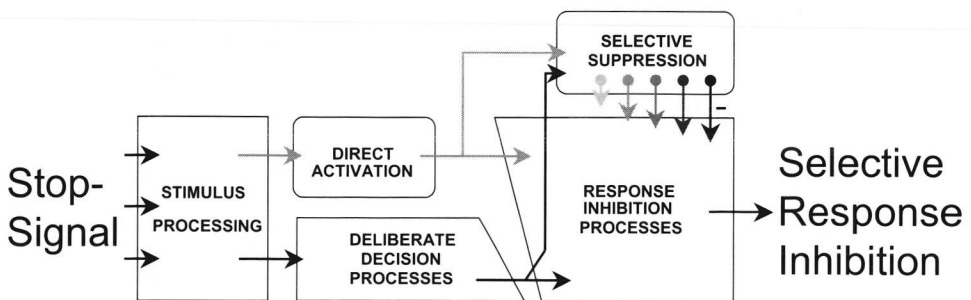


Figure 6.2: The dual-process model, adapted for selective response inhibition.



### *The stop task*

To examine whether the operation of selective go and selective stop processes are similar, we generalize the dual-process model to the domain of response inhibition (see Figure 6.2). Here, the selective stop process (resulting in selective response *inhibition*) receives activation from the deliberate route, but also from the direct route. Activation from the direct route is subsequently suppressed (resulting in selective response *disinhibition*), with a more or less fixed onset time. If processing along the deliberate route is rapid, then the operation of selective suppression comes into play relatively late, resulting in a relatively large congruency effect on SSRT. If the deliberate route is less rapid, then selective suppression operates more timely, such that the initial direct activation is selectively suppressed (sometimes so strongly that the net result is relative facilitation of the opposite response, as expressed in a reversed congruency effect; see Eimer, 1999). If the deliberate route is quite slow, then selective suppression operates relatively early, such that all initial activations have decayed by the time the deliberate route is finished (resulting in a zero congruency effect on SSRT). Thus, with highly discriminable stop signals the deliberate route can operate rapidly, resulting in a non-zero congruency effect on SSRT (positive or negative, depending on relative timing); with less discriminable signals the deliberate route operates slowly, resulting in a zero congruency effect.

#### *6.1.6 The present study*

If the present set of predictions receives support, then we can infer that stop processes operate much in the same way as go processes. Two control tasks are intended to establish that our experimental format will produce the typical performance patterns in (1) a regular Simon task (involving less and highly discriminable stimuli) and (2) a regular stop task involving simple response inhibition. In the regular Simon task, subjects are instructed to respond to the color of a rectangle and ignore its location; stimulus discriminability (red versus blue; yellowish green versus greenish yellow) will be varied between trial blocks to verify that the anticipated effects of response inhibition will be expressed in RT and delta-plot patterns. In the simple stop task, subjects are instructed to inhibit their response to the go task whenever they are presented with a stop signal (a colored rectangle). The location of the stop signal was irrelevant. SSRTs are calculated in accordance with conventional procedures to establish that typical findings regarding the efficiency of response inhibition will be replicated. Based on the selective stop literature, it was predicted that the position of the stop signal activates the stop process, which should result in a facilitation of stopping to congruent stop signals and delaying the stopping response to incongruent stop signals.

Next, the critical task is a selective stop task, where stop signals undergo the same manipulations as those in the regular Simon task. That is, subjects are instructed to refrain from responding to the primary task stimulus whenever a stop signal in a designated color is presented, but to continue to respond to the go task if presented with a stop signal in the other color. Again, stop-signal color is easy-to-discriminate (red versus blue) in one condition, but more difficult (yellowish green versus greenish yellow) in the other. As outlined above, if stop processes operate in the same way as go processes, then we predict a non-zero congruency effect on SSRT with highly discriminable signals and a zero congruency effect with less dis-

criminable signals. Any departure from this pattern indicates that go signals and stop signals are processed differently.

## 6.2 Method

### 6.2.1 Participants

Twenty-nine undergraduate students (19 females and 10 males, mean age = 22.6 years) participated to fulfill course requirements. All subjects reported to be right-handed and had normal or corrected-to-normal vision.

### 6.2.2 Apparatus and signals

Stimuli were presented and responses were collected with an IBM-compatible computer. In all tasks, a trial consisted of an imperative signal presented visually against a black background with a maximum of 500 ms with intervals varying randomly but equiprobably from 1250 to 1750 ms in steps of 125 ms. Left- and right-hand responses were collected from the 'z' and the '/' keys on the computer keyboard. The signals of the Simon tasks consisted of single colored vertical rectangles (height / width 3 x 1 cm) that could be red or blue in some conditions, and yellow or green in others (RGB-codes respectively 255-0-0; 0-0-225; 240-190-0; and 30-255-0). These imperative stimuli were presented 3.2 cm either to the right or to the left of a white fixation square (3 x 3 mm) that remained present during the task at central location such that the visual angles subtended by each bar were approximately 9.9° x 3.4°. The imperative signals of the primary task used in the stop tasks consisted of the single digits 0 to 9 presented at central fixation (height / width 1.5 x 1 cm, visual angles 1.7° x 1.1°). Digits were alternated with the fixation square. Colored rectangles identical to those described in the Simon tasks served as stop signals and were presented randomly but equiprobably on 30% of the trials to either the left or the right side of the primary task digit.

### 6.2.3 Tasks and design

#### *Simon tasks*

The subjects' task was to classify single rectangles according to color by responding with the left or right index finger as fast and as accurately as possible, independent of stimulus location. Two versions of the Simon task were administered that varied with respect to *color discriminability*; one version employed two highly discriminable colors, red and blue, and another version used less discriminable colors, yellow and green. For both highly and less discriminable conditions the location of the imperative stimulus was irrelevant to the choice task at hand. The spatial relationship between signal location and response key could either be *congruent* (CG: stimulus and response on ipsilateral sides) or *incongruent* (IG: stimulus and response on contralateral sides).

### *Stop-signal tasks*

The primary task or go task associated with the stop tasks was to classify single digits ranging from 0 to 9 according to an odd versus even criterion by pressing the left key ('z' key on the keyboard) or the right key ('/' key on the keyboard) or vice versa as fast and accurately as possible. On 30% of the trials, a stop signal was presented shortly after the onset of the primary signal, indicating that the response to the primary task was to be inhibited. The stop signal could appear equiprobably on a location that was either congruent (i.e., on the same location as) or incongruent with (i.e., opposite to) the response location associated with the primary signal. 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. Implementation of this tracking algorithm (Levitt, 1971) has been shown to produce percentages of successful response inhibition of approximately 50% (e.g., Osman, Kornblum, & Meyer, 1986).

There were two stop tasks. In the simple stop task only one stop-signal color (i.e., either all blue or all red) was employed upon which subjects had to refrain from responding to the primary task. An additional stop task, dubbed the selective stop task, was administered in two versions, both requiring subjects to refrain from responding to one stop signal but to ignore the other. In the selective stop task with high stop-signal discriminability subjects were to refrain from responding to the primary-task after presentation of a red stop signal and were to ignore the blue signals (or vice versa). In the selective stopping condition with less stop-signal discriminability subjects inhibited the motor response after presentation of a yellow stop signal and ignored the green stop signals (or vice versa). Note that in all stop tasks, stop-signal location, being either congruent or incongruent with respect to the correct response hand, was irrelevant to the task at hand.

#### *6.2.4 Procedure*

Groups of up to three subjects performed their tasks in a dimly lit, sound attenuated room in one session of about three hours. Participants were instructed to respond as fast and as accurately as possible. For the stop tasks, the subjects were instructed to avoid delaying their primary-task responses manual responses to increase the chances of stopping if a stop signal might occur. Furthermore, it was pointed out that stop-signal onset varied so that they would be able to stop to early stop signals whereas they would likely fail when stop signals were presented late. The experimental session started with the two versions of the Simon task. Each version of the Simon task consisted of two blocks of 120 randomly mixed trials per condition. The first block of trials of each version was for practice only and was not included for analysis. Initial color discriminability (i.e., high or less), as well as the signal color-response mapping (left or right) of the Simon task were counterbalanced across subjects.

The binary choice task employed in all stop tasks was practiced separately in one block of 100 trials before stop signals were introduced. The order of stop tasks (simple stopping, selective stopping with high stop-signal discriminability and selective stopping with less stop-signal discriminability) was counterbalanced across subjects. In the simple stop task, half of the participants received red stop signals only; the other half received blue stop signals only.

Participants completed two blocks of 400 trials each. The first block of trials was used for practice. The selective stop tasks with high and less stop-signal discriminability consisted of three blocks of 400 trials each. Again, the first block was for practice. Stop-signal color was counterbalanced across subjects. Performance feedback was given 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.

### 6.2.5 Data processing

The first four trials of every block of trials were viewed as warm-up trials and discarded. Individual mean reaction times (RTs) of correct trials were calculated after the removal of outliers from the RT distribution (i.e.,  $RTs > M + 2.5 SD$ ;  $RTs < M - 2.5 SD$ ) on a subject-by-subject basis. Stop-signal reaction times (SSRTs) for congruent and incongruent stop trials were estimated using the horse-race model (Logan & Cowan, 1984). The latency of the stop process can be estimated from the start and the finish of the stop process. The start of the stop process is under experimental control by the stop-signal delay, but the finish time has to be inferred from the observed go RT distribution. If responses are not stopped on  $n\%$  of the stop trials, then the finish of the stop process is on average equal to the  $n$ -th percentile of the go RT distribution. Finally, mean stop-signal delay is subtracted from this finish time to obtain an estimate of stop latency (see Logan, 1994). Stop-signal tracking based on inhibition rates of 50% provides stop latency estimates that are derived from the center of the go RT distribution, and are relatively insensitive to violations of the assumptions of the horse-race model (e.g., Band, van der Molen, & Logan, 2003; Logan, Schachar, & Tannock, 1997).

Distributional analyses of RT were used to examine the dynamics of selective response suppression in the Simon task. Delta plots are used to depict effect size (i.e., mean RT on IG trials minus mean RT on CG trials) as a function of response speed (i.e., average of mean RTs on CG and IC trials per RT quartile). RTs of correct responses in the Simon tasks were rank-ordered separately for CG and IC trials and divided subsequently into five equal-size speed bins (quintiles). Mean RT was determined for each quintile in each condition, as determined by the factorial combinations of Congruency and Signal Discriminability. For each RT quintile, the difference in RT between IG and CG conditions is plotted on the Y-axis against the mean of the CG and IG RTs in that quintile. With weak inhibition only the slower IG responses benefit from selective suppression, while with stronger inhibition, the benefit for IG responses is more pronounced, and extends to faster portions of the CDF (Ridderinkhof, 2002a).

Thus, in delta plots for RT, the slopes between quartile points turn from positive to more negative relatively late when suppression is weak, and progressively earlier when suppression is stronger. Compared to the faster condition (highly discriminable stimuli), for the slower condition (less discriminable stimuli) suppression will be expressed in earlier portions of the RT distribution. Thus, delta plots are predicted to turn negative in earlier quintiles for less- compared to highly discriminable stimuli.

### 6.3 Results

#### 6.3.1 Simon tasks

Missing responses (percent omissions < .5%) were discarded from the data. Mean RTs of correct trials and choice error percentages were calculated per subject, discriminability condition, and location congruency. RTs and square roots of choice error percentages were analyzed in a 2 x 2-factorial ANOVA design with Signal Discriminability (high vs. less) and spatial relation between stimulus location and designated response side (henceforth referred to as Congruency; CG versus IG) as within-subjects factors (see Table 6.1).

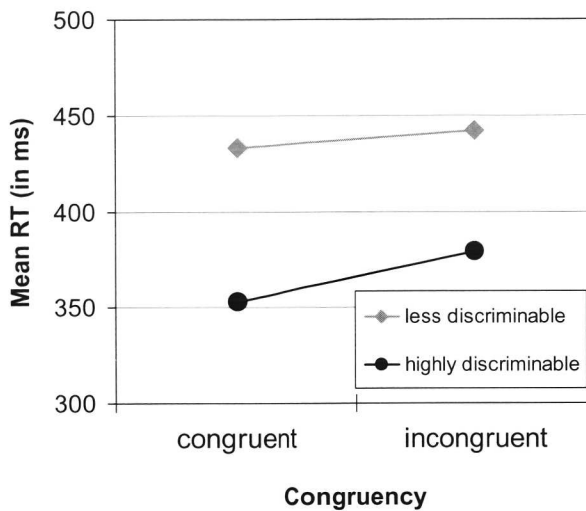


Figure 6.3: Mean RT effects of signal discriminability (high vs. less) and congruency (congruent vs. incongruent) in the standard Simon task.

Table 6.1: Mean reaction times (RT in ms), error percentages, and standard deviations (in parentheses) per discriminability (high vs. less) and congruency (CG vs. IC) in the Simon tasks.

| Imperative stimuli   | Signal-response congruency |           |             |           | Effect size |
|----------------------|----------------------------|-----------|-------------|-----------|-------------|
|                      | Congruent                  |           | Incongruent |           |             |
|                      | RT                         | Error (%) | RT          | Error (%) |             |
| highly discriminable | 353 (35)                   | 5 (4)     | 379 (40)    | 9 (8)     | 26          |
| less discriminable   | 433 (48)                   | 10 (7)    | 442 (49)    | 14 (13)   | 9           |
| effect size          | 80                         |           | 63          |           |             |

First, Signal Discriminability produced a significant main effect on RT,  $F(1, 28) = 133.6, p < .001$ , and on choice errors,  $F(1, 28) = 11.4, p = .002$ . On average, RTs from the condition with difficult-to-discriminate bar colors were 72 ms slower than RTs from the condition with the easy-to-discriminate bar colors.

Second, Congruency between the location of the respond signal and response button exerted a significant main effect on RT,  $F(1, 28) = 29.3, p < .001$ , and on choice errors,  $F(1, 28) = 6.8, p = .014$ , reflecting faster and more accurate responses on CG (393 ms) than IC (411 ms) trials.

Third, the under-additive interaction between Signal Discriminability and Congruency was significant for RT (see Figure 6.3),  $F(1, 28) = 11.3, p = .002$ , but was absent with respect to the error data,  $F(1, 28) = 2.4, p = .130$ . The cost of the need to respond on an IC trial was 26 ms for highly discriminative signals, but only 9 ms for less discriminable signals. The direction of the accuracy effects discarded interpretations of the RT findings in terms of speed/accuracy trade-off. These findings are consistent with Hommel (1993) who demonstrated decreased Simon effects in every experimental manipulation that markedly increased the temporal distance between the coding of the relevant stimulus information (color) and that of the irrelevant stimulus location.

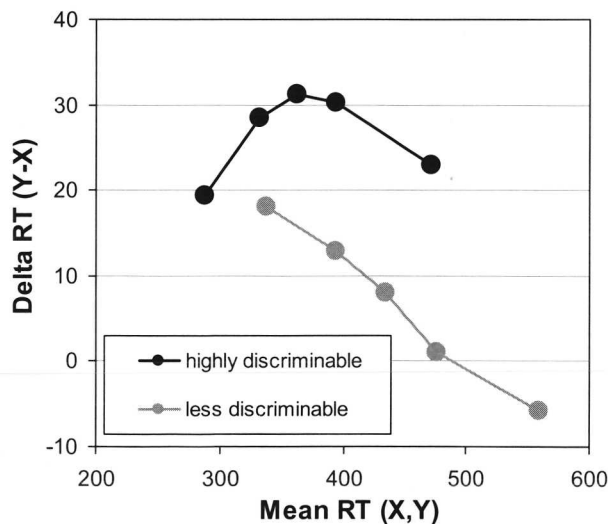


Figure 6.4: Delta plots for response speed plotting effect size (IC RT – CG RT) as a function of response speed. Response speed is expressed in RT quintile scores.

The second set of ANOVAs focused on the effects of Discriminability on the slopes of the delta plots to explore the dynamics of selective suppression of response activation associated with the irrelevant positional aspects of the imperative signals (depicted in Figure 6.4). Analyses of delta-plot slopes yielded significant main effects of Discriminability,  $F(1, 28) = 4.9, p = .035$ , Segment (1 to 4),  $F(1, 28) = 4.9, p = .035$ , and most importantly their interaction,  $F(3, 84) = 2.8, p = .043$ . As can be seen in Figure 6.4, the slopes of the two discriminability

conditions diverge in early segments ( $q1-2$ ,  $F(1, 28) = 3.6$ ,  $p < .001$ ;  $q2-3$ ,  $F(1, 28) = 2.3$ ,  $p = .028$ ) whereas the slopes parallel in later segments ( $q3-4$ ,  $F < 1$ ;  $q4-5$ ,  $F < 1$ ).

These findings suggest that the active suppression of response activation that is associated with the irrelevant location dimension of the stimulus needs time to build up, and that this active suppression is more prominent in the Simon task with less discriminable stimuli than with highly discriminable stimuli, as indicated by the negative slopes.

### 6.3.2 Stop-signal tasks

The results of the simple and selective stop tasks are summarized in Table 6.2.

#### *Response execution*

Analyses of the responses to the primary-task digits indicated that go-signal RT varied between stop-task conditions,  $F(2, 27) = 8.8$ ,  $p < .001$ . Error percentages on no-signal trials did not differ between stop tasks,  $F(2, 27) = 1.4$ ,  $p = .26$ . Orthogonal contrast analysis revealed that mean go RTs in the simple stop task were significantly slower compared to the mean go RTs computed over both selective stop tasks,  $F(1, 28) = 12.2$ ,  $p < .01$ . Most important, primary-task RTs did not differ between the two selective stopping tasks ( $F < 1$ ), so the manipulation of stop-signal discriminability did not influence subjects' response latencies to primary-task signals.

#### *Response inhibition*

The probabilities of responding given a stop signal were .49 for simple stopping, .51 for selective stopping with easy-to-discriminate colors, and .55 for selective stopping with difficult-to-discriminate colors. Thus, the tracking algorithm did result in an observed response rate on stop trials close to the anticipated 50%.

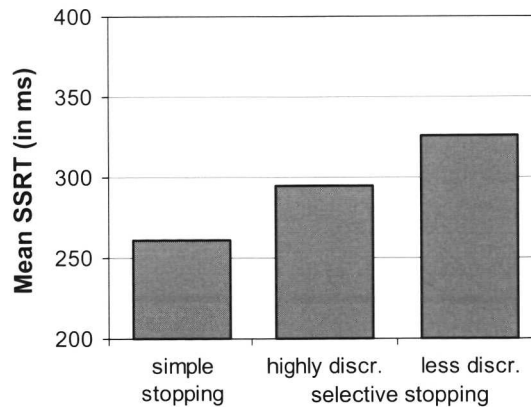


Figure 6.5: Stopping latencies in the simple and selective stop tasks.

First, a within-subject analysis on mean stop-signal RTs yielded a main effect of Stop task,  $F(2, 27) = 15.2, p < .001$ . Orthogonal contrast analysis showed that selective inhibition latencies (310 ms) were significantly slower than simple stopping (260 ms),  $F(1, 28) = 28.4, p < .001$ . Selective stopping to less discriminable stop signals (326) was slower than stopping to highly discriminable stop signals (294 ms),  $F(1, 28) = 9.2, p = .005$ .

Table 6.2: Mean go-signal reaction time (Go RT in ms), error percentages, signal-respond reaction times (SRRT), stop-signal reaction times (SSRT), and standard deviations (in parentheses) per congruency (congruent vs. incongruent) and stop-signal discriminability (high vs. less) in the simple and selective stop tasks.

| Stop task   | Stop signal-response congruency |           |           |          |             |          | Effect size |
|-------------|---------------------------------|-----------|-----------|----------|-------------|----------|-------------|
|             | Go trials                       |           | Congruent |          | Incongruent |          |             |
|             | Go RT                           | Error (%) | SRRT      | SSRT     | SRRT        | SSRT     |             |
| Simple      | 502 (57)                        | 8 (3)     | 474 (51)  | 256 (49) | 480 (51)    | 265 (58) | 9           |
| Selective   |                                 |           |           |          |             |          |             |
| highly disc | 485 (56)                        | 8 (3)     | 482 (51)  | 301 (57) | 484 (57)    | 287 (48) | -14         |
| less disc   | 488 (65)                        | 9 (3)     | 497 (70)  | 326 (77) | 505 (73)    | 326 (74) | 0           |

### *Simple stopping*

A within-subject analysis with Congruency as a factor (congruent vs. incongruent) revealed a significant main effect on Stop-signal RT for simple stopping,  $F(1, 28) = 4.5, p = .04$ . On average, responses on trials with a stop signal appearing on the location opposite to (i.e., incongruent with) the location of the response hand indicated by the go-task signal were inhibited 9 ms slower than on congruent trials. This finding is compatible with the prediction that the position of the stop signal facilitates the speed of stopping if presented on the same side as the response hand.

### *Selective stopping*

A comparison of stop latencies confirmed that responses were stopped significantly slower when stop-signal discriminability was less (326) compared to highly discriminable stop colors (294 ms),  $F(1, 28) = 9.17, p = .005$ . The main effect of Stop-signal congruency on selective stopping latencies just failed to reach significance  $F(1, 28) = 3.0, p = .09$ . Importantly, a significant interaction between Stop-signal discriminability and Stop-signal congruency was obtained,  $F(1, 28) = 4.1, p = .05$ , indicating that the effect of Stop-signal congruency on stop latencies differed between the two Stop-signal discriminability conditions as plotted in Figure



6.6. Post-hoc comparisons indicated that with easy-to-discriminate stop colors, stopping to congruent stop signals was significantly *slower* by 14 ms compared to incongruent stop signals,  $F(1, 28) = 6.5, p = .016$ . Selective stopping latencies to congruent and incongruent stop-signals in the selective stopping task that employed less discriminable stop signals did not differ,  $F < 1$ .

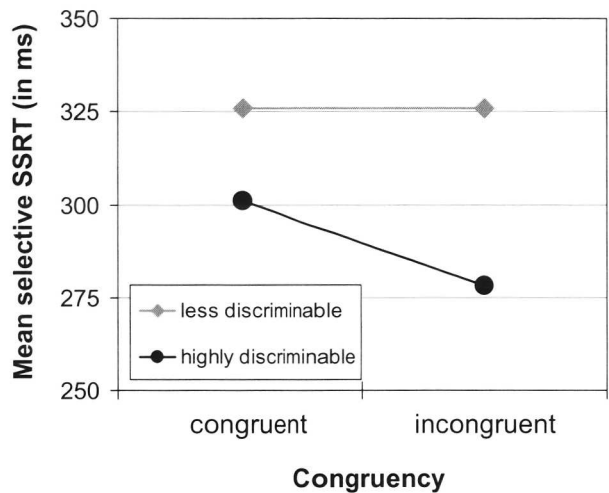


Figure 6.6: Mean effects of signal discriminability (high vs. less) and congruency (congruent vs. incongruent) on selective stop latencies.

Table 6.3: Mean RT (ms), error percentages, and standard deviations (in parentheses) on invalid stop trials by congruency (congruent vs. incongruent) and discriminability (high vs. less) in the selective stopping tasks.

| Stop-signal<br>discriminability | Stop signal-response congruency |            |             |            |
|---------------------------------|---------------------------------|------------|-------------|------------|
|                                 | Congruent                       |            | Incongruent |            |
|                                 | Invalid RT                      | Error (%)  | Invalid RT  | Error (%)  |
| high                            | 551 (81)                        | 6.1 (4.1)  | 552 (73)    | 10.7 (5.8) |
| less                            | 579 (102)                       | 10.7 (7.4) | 604 (109)   | 15.2 (9.5) |

## 6.4 Discussion

This study was designed to examine whether go and stop processes are similar in nature. The conceptual framework provided by the dual-process model and the activation-suppression hypothesis, that have been used extensively to explore activation and suppression in conflict tasks, were generalized here to study activation and suppression in stop processes as well. For go processes, activation and suppression were verified using congruency relations and a stimulus-discriminability manipulation in a Simon task; for stop processes, activation and suppression were examined by using the same manipulations in the stop task.

### 6.4.1 Simon tasks

The outcomes of the regular Simon tasks replicated earlier findings reported in the existing literature (e.g., Hommel, 1993; 1994). As anticipated, subjects responded faster in blocks of trials that employed highly discriminable imperative signals compared to less discriminability signals. Typical for Simon tasks, Stimulus-Response congruency had a substantial effect on the speed of response execution; responses to congruent trials were significantly faster than on incongruent trials. Moreover, analysis of RT patterns revealed an *under additive* interaction between the effects of Congruency and Stimulus Discriminability, indicating a decreased Simon effect under less discriminability conditions. The difference in RT between spatially congruent and incongruent trials (i.e., the Simon effect) was about three times larger when signal discriminability was high (26 ms) than when it was less (9 ms). These values are similar in magnitude compared to the results reported earlier by Hommel (1994, experiment 1), who obtained congruency effects of 29 ms and 12 ms under high vs. less signal discriminability conditions. In a series of experiments, Hommel studied the Simon effect in blocks with lowered signal quality or delayed signal formation, experimental manipulations known to slow down the processing of relevant information. The observation of attenuated Simon effects associated with manipulations that prolong RT led Hommel to suggest that location-induced response activation automatically decays over time (see also Hommel, 1993). In terms of the dual-process model, activation elicited by the irrelevant positional feature of the imperative signal along the direct activation route has decayed by the time the deliberate route produces activation for the response based on stimulus color.

Distinct from the notion of automatic decay, the negative-going slopes presented in the delta plots evidence the involvement of active suppression of task-irrelevant response activation (Ridderinkhof, 2002a). Trials presented in the less discriminability condition displayed relatively stronger suppression effects, as indicated by the negative slopes of the delta plot. Comparing the delta plots of the two discriminability conditions it can be seen that the slopes parallel at the slower quartiles suggesting that suppression of irrelevant response activation became effective also in the Simon task employing highly discriminable signals, but only at later stage of response execution. This interpretation is consistent with the results of electrophysiological studies supporting the notion of direct activation and subsequent selective suppression of response activation associated with irrelevant stimulus features, or '*facilitation-followed-by-inhibition*' (Eimer, 1999; Eimer & Schlaghecken, 1998).

#### 6.4.2 *Stop-signal tasks*

The stimuli employed in the Simon task further served as stop signals in the simple and selective stop tasks. As predicted, simple stopping to just one stop signal was faster than stopping selectively to one of two stop signals. An advantage of simple over selective inhibitory motor control is in agreement with previous results on simple and selective stop-signal inhibition with different versions of the stop task (cf. De Jong et al., 1995; Logan et al., 1986; Van den Wildenberg & van der Molen, 2003a). Increased latencies associated with selective stopping may be suggestive of increased demands on cognitive control processes as imposed by the selective inhibition task (cf. Bedard et al., 2002; Van den Wildenberg & van der Molen, 2003a). The standard simple inhibition paradigm requires stop-signal detection, upon which the response to the primary-task stimulus is to be aborted. This simple stop condition bears a resemblance to the classic Donders A task (Donders, 1868/1969) that requires a simple reaction to the presentation of a stimulus. Similarly, the requirement to distinguish between two tones in the selective stop tasks could be interpreted as a Donders C task. Compared to the simple A task, processing of the C task involves the additional stage of stimulus discrimination, which makes the selective inhibition task more demanding (see also Riegler, 1986).

Comparison of psychophysiological data obtained from selective and simple stop tasks have led several researchers to suggest that simple and selective inhibition are mediated by two functionally distinct mechanisms (Logan, 1994, see also De Jong et al., 1995; but see Band and van Boxtel, 1999). Developmental studies are relevant in the discussion on inhibitory mechanisms, because they have presented evidence that both simple and selective stopping improved throughout childhood but at different rates (Bedard et al., 2002; Van den Wildenberg & van der Molen, 2003a). This developmental fractionation of simple and selective inhibition is inconsistent with the notion that speeded information processing is mediated by a single global mechanism (e.g., Cerella & Hale, 1994).

It should be noted that the discriminability level of the stop signals in the selective stop tasks did not affect primary-task performance. Although selective stopping was substantially slower to one of two harder to discriminate stop signals as opposed to an easy to discriminate stop signal, go-signal RTs did not differ significantly between easy and difficult stop-signal discriminability conditions. This finding suggests that the discriminability demands imposed upon selective stop-signal processing did not interfere with the processing of the primary task.

#### 6.4.3 *Stop-signal processing vis-à-vis go-signal processing*

The primary aim of the present study was to test the hypothesis that stop processes are similar in nature to go processes. We used the Simon task which has proven to be useful in investigating the nature of go processes, and applied Simon-like factorial manipulations to stop signals in a simple stop task and two selective stop tasks.

First, the observed congruency effects of stop-signal location on simple stop latencies may be interpreted in terms of the dual-process model (Kornblum et al., 1990). Probably, the location of the stop signal unconditionally triggers the matching location representation via the fast direct route, like in the standard Simon tasks. If the location representation that is triggered by this automatic process matches the location of primary-task processing, the stop

response is enhanced. This boost of inhibitory processing is absent in case of incongruence between stop-signal location and primary-task response. Alternatively, the finding of slower simple stop latencies to incongruent stop signals is also in accord with capacity hypotheses formulated by Ridderinkhof et al. (1999) and Kramer et al. (1994). Accordingly, the simple stop process might be hampered if, at the same time, activation that is associated with the irrelevant location of the stop signal is being suppressed.

Second, we observed a zero congruency effect with less discriminable signals, and a non-zero congruency effect with highly discriminable signals on RT as well as on SSRT. These results confirm our conjecture that the speed of go processes and stop processes triggered by Simon signals are affected by irrelevant aspects of the signal. Most interestingly, congruency effects in the selective stop task with high stop-signal discriminability showed the reversed pattern, that is, selectively stopping to incongruent stop signals was found to be slower compared to congruent stop signals. An interpretation of this striking congruency pattern (a reversed Simon effect) might be related to the timing of the inhibitory response relative to the influence of direct response activation generated by the position of the stop signal. Recall that the inhibition dynamics in the standard Simon tasks, as revealed by the delta plots, point in the direction of '*activation-followed-by-suppression*' or an initial enhancement followed by an active suppression of automatic response activation. This selective suppression of location-based response activation was indicated by negative congruency effect in the later end of the RT distribution. Along similar lines, the present reversal of congruency effects on selective stop latencies could be explained in terms of this relatively strong suppression of location based response activation. Besides mere stop-signal detection, as in the simple stop task, the subject has to engage a selective stop process based upon the identification of the stop signal. This signal identification process by the controlled route is by-passed by initial processing of location-based direct response activation. Although using the fast direct route would boost the stop process, as it did in the simple stop task, this strategy would be disadvantageous in the selective stop tasks, as only half of the stop signals were designated as valid stop signals; the other half of the stop signals are invalid and require a primary-task response. In order to avoid fast stopping to invalid stop signals as required by the instructions, subjects may block processing by the fast route in favor of the slower but safer route of controlled identification of the stop signal. The present congruency effects seems to support the notion that subjects suppress fast route processing, resulting in a relative facilitation of inhibitory responses to incongruent stop-signals.<sup>2</sup>

Finally, the observation of annihilated effects of congruency on the speed of stopping associated with stop signals that were harder to discriminate is in accord with the dual process

<sup>2</sup> However, an alternative interpretation of the reversed Simon effect on selective SSRTs to highly discriminable stop signals can be formulated also. It could be argued that, in stop-signal trials, the location of the stop signal triggers the stop process of the corresponding primary-task response (e.g., a stop signal presented to the right suppresses a right-hand response). As a result, primary-task response activation will be attenuated when countermanded by congruent compared to incongruent stop signals. Thus, congruent stop signals will reduce ipsilateral response activation that is associated with the primary task to a larger extent than incongruent stop signals. However, the inhibition process should be triggered by identity-based, not location based information of the stop signal. The stop-signal process that is triggered by a valid congruent stop signal has to countermand a less activated response because response activation is already suppressed by the congruent location of the stop signal. Previous studies have indicated that reduced response readiness is associated with delayed stopping (Van den Wildenberg & van Boxtel, van der Molen, 2003; Van den Wildenberg, van der Molen, & Logan, 2002). This might explain why selective stopping latencies are slower to congruent compared to incongruent stop signals.

model. Selective stopping to one of two hard-to-discriminate stop signals was slowest whereas stop-signal delays were shortest of all tasks. These prolonged intervals between stop-signal presentation and the (selective) inhibitory response renders it very likely that the effects of stop-signal location on response activation via the fast direct route are decayed by the time the subject has identified the stop signal as a valid or invalid, which resulted in comparable selective stop latencies to congruent and incongruent stop signals.

The present results indicate that stop-signal processing can be described by a dual processing architecture that incorporates a direct location-based route and a controlled identification-based route for response inhibition. This conjecture may provide a handle for future studies aimed at providing a deeper understanding of the nature of stop-signal inhibition.