Research Article

Processing of Global and Selective Stop Signals

Application of Donders' Subtraction Method to Stop-Signal Task Performance

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Abstract. This paper applied Donders' subtraction method to examine the processing of global and selective stop signals in the stop-signal paradigm. Participants performed on three different versions of the stop task: a global task and two selective tasks. A global task required participants to inhibit their response to a go signal whenever a stop signal was presented (*Stop-a task*). A selective stop task required participants to inhibit to one stop signal but not to the other (*Stop-c task*). Another selective stop task required them to inhibit when the response indicated by go and stop signals was the same but not when they were different (*Stop-b task*). Stop-signal reaction time (SSRT) was shortest for Stop-a and longest for Stop-b, with intermediate values for the Stop-c task. Additional control experiments that manipulated stop probability confirmed the robustness of global and selective stopping latencies even when the stop-signal probability varied. The current findings contribute to the conclusion that Donders' subtraction method provides a useful tool for estimating the durations of subprocesses that together comprise SSRT.

Keywords: stop-signal paradigm, response inhibition, reaction process, subtraction method, inhibitory control

Efficient interaction with the environment requires that intended or ongoing actions can be quickly aborted or inhibited in response to sudden environmental changes. The stop-signal paradigm has been applied successfully to study manifestations of response inhibition across widely different domains (Logan & Cowan, 1984; for reviews, see Logan, 1994; Verbruggen & Logan, 2008), including eye movements (Cabel, Armstrong, Reingold, & Munoz, 2000) and response preparation (Li, Krystal, & Mathalon, 2005). In the stop-signal paradigm, participants usually perform a speeded choice reaction time (RT) task that requires a binary button-press response to a visual stimulus; the go signal. For example, they press a button with the left hand after seeing an "X" and they press a right-hand button when presented with an "O". On some trials, the onset of the go signal is followed shortly by a stop signal (usually a brief tone) that informs the participant to withhold the press response. Successful stopping on these stop trials depends on the length of the interval between the go signal and the stop signal (i.e., the stop-signal delay). Response inhibition is relatively easy when stop-signal delay is short but stopping becomes increasingly difficult or virtually impossible with longer stop-signal delays.

Information processing on stop-signal trials has been conceptualized in terms of a race between go and stop processes in which the process that finishes first determines whether the response is executed or inhibited (Logan & Cowan, 1984). If the go process finishes first, the motor response will be executed. Conversely, if the stop process wins the race, the go response will be countermanded. Given the assumptions associated with the race model, the finish of the stop process can be estimated from the distribution of RTs on go trials. The left side of the go RT distribution represents fast responses that escape inhibition (*stop-respond trials*) while the right side represents slow responses that will be inhibited (*stop-inhibit trials*). If a given participant actually failed to inhibit on n% of the stop trials, the finishing time of the stop process will approximately be equal to the nth percentile of the go RT distribution. The mean stop-signal delay is then subtracted from the nth percentile of the go RT distribution, resulting in an estimation of the latency of the stop process (SSRT; see Band, van der Molen, & Logan, 2003; Logan, 1994; Logan & Cowan, 1984; see Figure 1 for a graphical representation of the race model). With SSRT as index of inhibitory efficiency, the stop-signal paradigm provides clear advantages over other experimental procedures that assess the ability to inhibit, such as the go/nogo task.

Although the race model yields an accurate description of stop performance (Band et al., 2003), it does not provide

DOI: 10.1027/1618-3169/a000019

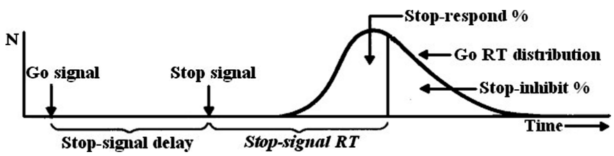

Figure 1. Graphical representation of the race model. The curve presents the distribution of RTs on go trials that is bisected by the finishing time of the stop process (vertical line). The left part of the distribution consists of RTs to go signals that are too fast to be inhibited (the go process is faster than the stop process), while the right part presents go RTs belonging to responses that were slow enough to be inhibited (the stop process is faster than the go process). SSRT is derived by subtracting mean stop-signal delay from the finish time of the stop process.

insight into the nature of the processes that constitute the stop-signal RT (cf. Logan, 1994). To increase our understanding of stop-signal inhibition, several behavioral studies combined the stop-signal paradigm with conflict situations such as the Eriksen task that require inhibition to solve response conflict (Eriksen & Eriksen, 1974). The arrow version of the Eriksen task, for example, requires the selection of an overt response based on the direction of a target arrow that is flanked by arrows pointing in the same (congruent) or opposite (incongruent) direction. RT to target arrows typically is increased with incongruent flankers compared to congruent or neutral flankers. Interestingly, incongruent flankers prolong SSRT compared to congruent flankers, indicating that the response inhibition resolving the conflict and the inhibition required by the stop signal share a common inhibitory mechanism (e.g., Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Ridderinkhof, Band, & Logan, 1999; Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005; Verbruggen, Liefooghe, & Vandierendonck, 2004, 2006).

One of the first attempts to investigate the neurophysiological mechanisms of stopping control is a study by de Jong and colleagues who recorded brain potentials (EEG) during performance on different versions of the stop-signal paradigm (de Jong, Coles, & Logan, 1995). *Global inhibition* in the standard stop task was compared to inhibition in a stop-change task (*stop-change inhibition*, i.e., the inhibited response is followed by an alternative response) and to *selective inhibition* of only one of the two manual responses. In the latter condition, subjects were instructed to withhold responses with the right hand when hearing a stop signal but not with the left hand. de Jong and colleagues reported that stop-change and selective inhibition took substantially longer than global inhibition. Moreover, their psychophysiological findings led them to propose two separate inhibitory mechanisms; a central, but relatively slow operating, cortical mechanism and a peripheral midbrain mechanism that is used when responses escape cortical inhibition. van Boxtel, van der Molen, Jennings, and Brunia (2001) amassed evidence for a single stopping mechanism and this view was supported by an extensive review and a model that emerged from Band and van Boxtel (1999).

The present study investigates the nature of response inhibition by complicating the stopping process. Our strategy was inspired by the assumption that in essence stop-signal processing is analogous to a reaction process. That is, stopping in the global stop-signal task is analogous to reacting in a simple RT task (Logan, 1994); there is only one signal (usually a tone) and only one (stop) response. In the selective stop task employed here, participants were presented with two stop signals; a valid stop signal upon which they should inhibit and an invalid signal that should be ignored (see also Bedard et al., 2002; Riegler, 1986). Likewise, selective stopping in this sense is analogous to a go/nogo situation (Riegler, 1986, but see Logan, 1994); there are two signals but only one signal requires a (stop) response. The basic idea is that the stop process, like the reaction process, consists of a series of component processes that can be examined by using tools derived from the experimental psychology literature. Both the response process and the inhibition process start with detecting a stimulus (respectively, the go signal or the stop signal) and end with the actual response execution or inhibition implementation (van den Wildenberg & van der Molen, 2004a). Intermediate stages like stimulus identification and response selection (Sternberg, 1969) demand some time that may affect the total processing time that is reflected by going (go RT) and stopping latencies (SSRT). In a previous study, we performed a Sternberg (1969) additive-factors analysis of stop-signal processing that suggested that stimulus similarity and S-R compatibility affect independent stages of the choice reaction process that were labeled "stimulus encoding" and "response selection" (van den Wildenberg & van der Molen, 2004a). Subsequently, the stopping process was manipulated by selective stopping instructions and the results showed robust effects of S-R compatibility on the stopping process and less pronounced effects of stimulus similarity (see van den Wildenberg & van der Molen, 2004a, for a more detailed description of the tasks). Most importantly, these factors did not interact, suggesting that they influenced separate stages of stop-signal processing. These results illustrate that procedures relying on the "linear stages" assumption provide new insights into the nature of the stopping process, here its structural properties.

In this paper we extend this approach by applying Donders' subtraction method (Donders, 1868/1969) to assess the nature of stop-signal processing using three stop task variants. Like the additive-factors method, the subtraction method assumes that the time elapsing between stimulus presentation and response completion consists of the durations of linear series of independent processing stages. Following the subtraction method, the duration of a particular processing stage can be estimated by comparing RTs yielded by two tasks - one task that includes the stage of interest and a corresponding task that does not include that particular stage. Differences in RT provide an estimate of the duration of the processing stages that the two tasks do not share (for reviews, see Gottsdanker & Shragg, 1985; Sternberg, 2001; Ulrich, Mattes, & Miller, 1999; van der Molen, Bashore, Halliday, & Callaway, 1991). In this study, a typical global stop task, dubbed the *Stop-a task*, required participants to inhibit their manual responses to the go signal whenever a stop signal was presented (corresponding to a Donders-a task or simple RT task). A selective stop task, or *Stop-c task*, required participants to inhibit their go responses when one stop signal occurred, but not when the other stop signal was presented (analogous to a Donders-*c task* or a disjunctive task). Stopping in this task usually takes more time than in global stop tasks (Bedard et al., 2002; van den Wildenberg & van der Molen, 2004b). Finally, a selective stop task, or *Stop-b task*, required participants to inhibit their right motor response to one stop signal and left motor response to the other stop signal, that is to inhibit the response if the go and stop signals are mapped onto the same hand but not when mapped onto different hands (or *b-task* in Donders' terminology or a choice RT task). Previous studies employing a Stop-b task showed stop-signal latencies that were much longer than inhibition times observed for global stopping (e.g., Coxon, Stinear, & Byblow, 2007; Logan, Kantowitz, & Riegler, 1986). We applied Donders' subtraction method to the analysis of global and selective SSRT. Subtracting Stop-a latency from Stop-c latency should provide an estimate of the duration of the stop-signal discrimination stage and likewise, subtracting Stop-c latency from Stop-b latency should yield an estimate of the response-mapping stage involved in selective inhibition in the Stop-b task. The first experiment is followed by two additional experiments that were designed to rule out confounds that might have emerged from different proportions of go trials in the Stop-a task versus both selective tasks (Experiment 2) and the use of a single stop color versus two stop colors in the Stop-a task (Experiment 3).

Experiment 1

Method

Participants

Eighteen students (11 women, *M* age 21.3, *SD* = 3.3 years) of the University of Amsterdam participated in this experiment for course credits. All had normal or corrected-to-normal vision and were right-handed.

Materials and Stimuli

Participants were seated in a comfortable chair facing a computer screen at a distance of about 1.5 m. Each trial started with a white fixation cross (3 × 3 mm) appearing in the center of the screen for 500 ms followed by the go signal. The go signal consisted of a white left- or a right-pointing arrow (2.2 × 1.8 cm) presented centrally for 1,000 ms against a dark-gray background. The intertrial interval varied randomly between 1,750 and 2,250 ms, in steps of 50 ms. During this interval, the fixation cross was presented. The response buttons consisted of the keyboard keys "z" (left) and "/" (right). Motor responses were collected until the offset of the arrow stimulus.

A color change of the white arrow to pink or blue indicated a stop signal. The stop-signal delay (i.e., the interval between the onset of the go signal and the stop signal) of the first stop trial in the practice block was set at 150 ms and was dynamically adjusted throughout the experiment as a function of the stop performance of the participant; upon successful stopping on valid stop signals (see Experimental Tasks), stop-signal delay increased with 25 ms, whereas a failure to inhibit decreased stop-signal delay on the next stop trial by 25 ms (Levitt, 1971). This tracking algorithm was set to ensure 50% failed inhibitions which yields accurate estimates of SSRT (Band et al., 2003).

Experimental Tasks

Stop-a Task

Participants were instructed to press the left key with the left index finger and the right key with the right index finger to white arrows pointing left and right, respectively (82% go trials). Presentation of right- and left-pointing arrows varied randomly within a block of trials. On 18% of the trials the white arrow turned either pink or blue (equiprobable), indicating a global stop signal. Participants should refrain from responding upon presentation of a stop signal. They were told to give way to the go signal and not to delay responding in anticipation of a stop signal. In addition, they were informed about the tracking algorithm and it was explained that a "waiting strategy" would not increase the success of stopping. The Stop-a task consisted of four experimental blocks of 100 trials each.

Stop-b Task

Participants were instructed to perform the go task as described above but now blue and pink stop signals were each mapped onto a hand. For half the subjects the pink stop signal was mapped onto the right hand and the blue stop signal onto the left hand. The mapping was reversed in the other half. Participants were instructed to withhold their response but only if the go signal and stop signal were mapped onto the same hand (e.g., in the case that the left arrow required a left-hand response and the blue stop signal was associated with the left hand). These trials are coined *valid stop trials*. Conversely, on trials where go and stop signals were mapped onto different hands, subjects were instructed not to refrain from responding and to press the button associated with the go signal. The occurrence of a left-pointing arrow in conjunction with a pink stop signal coupled with the right hand illustrates such an *invalid stop trial*. Again, the occurrence of a valid stop signal was 18%. Invalid stop signals occurred on 17% of the trials (a total of 35% stop signals). The tracking algorithm adjusted stop-signal delays on valid stop trials only and stop-signal delay on invalid stop trials followed the current valid delay. Participants performed four experimental blocks of 100 trials.

Stop-c Task

Presentation of go (65%) and stop trials (35%) was similar to the Stop-b described above, as were the trial numbers and the

Table 1. Percentages of choice and omission errors, and median RT on go trials, percentage of stop-respond trials, and stop-respond RT, stop-signal delay, and stop-signal RT (SSRT) on valid stop trials, and percentage of omissions, invalid RT, fast invalid RT, and slow invalid RT on invalid stop trials per stop task in Experiment 1 (*SD* between parentheses)

	Stop task		
	Stop-a	Stop-b	Stop-c
Go trials			
% Choice errors	0.8 (1.0)	0.5 (0.5)	0.9 (1.1)
% Omissions	0.6 (1.0)	0.2 (0.3)	0.3 (0.4)
Go RT	403 (78)	422 (123)	414 (96)
Valid stop trials			
% Stop-respond	48.9 (2.1)	48.8 (3.0)	48.4 (2.4)
Stop-respond RT	373 (67)	408 (114)	384 (84)
Stop-signal delay	180 (39)	151 (44)	166 (47)
SSRT	221 (26)	260 (28)	240 (34)
Invalid stop trials			
% Omissions	–	2.3 (2.5)	1.1 (1.4)
Invalid RT	–	558 (185)	481 (138)
Fast invalid RT	–	363 (32)	362 (29)
Slow invalid RT	–	654 (135)	551 (103)

tracking procedure. Participants discriminated between pink and blue stop signals and inhibited their response only to one valid stop color (e.g., blue) and responded to the direction of the arrow if presented with an invalid stop color (e.g., the arrow turning pink). Half the participants inhibited to blue whereas the other half stopped to pink signals. Again four blocks were administered.

Procedure

The Stop-a, Stop-b, and Stop-c tasks were administered in one session and task order was counterbalanced across participants. Every task started with one practice block that was excluded from further analyses. Blocks of trials lasted about 5 minutes each and were followed by performance feedback. Short breaks were given between blocks and a longer rest was given between tasks.

Data Analysis

Data of 16 participants were included in the analysis. Two participants were excluded; one displayed a disproportionate global SSRT of 292 ms and one showed large variation in RTs over blocks of trials (mean difference between blocks approximately 150 ms). Repeated-measures analyses of variance (ANOVA) were conducted on latency measures and on error percentages. Multiple comparisons were used to confirm effects. Degrees of freedom and *p*-values were adjusted using Greenhouse-Geisser corrections. Since error percentages are not normally distributed, tests were performed on square rooted error values. The horse-race model was used to obtain estimates of stopping latencies, that is, SSRTs (see Figure 1 and Introduction for details). The percentage of stop-respond trials was computed to verify operation of the tracking algorithm. Finally, the percentages of omission errors and RTs were computed for invalid stop trials in the Stop-b and Stop-c tasks and compared to RTs on go trials.

Results and Discussion

Response Execution

Median RT[1] and error percentages on go trials were calculated for all three stop tasks and are listed in the upper panel of Table 1. Percentages of errors and omissions were low, below 1%, for all tasks, indicating that go responses were highly accurate. Analysis of go RT yielded a significant main effect of Task, $F(2, 30) = 4.16$, $p = .03$. Pairwise comparisons indicated that participants responded slightly faster on go trials in the Stop-a task compared to the Stop-b task (403 vs. 422 ms, $p = .02$).

Response Inhibition

Valid Stop Trials

See middle panel of Table 1 for valid stop results. The percentages of stop-respond trials were around 49% and did not differentiate between Tasks ($F < 1$). This verified that the tracking algorithm worked very well. A premise of the race model is that stop-respond RT is shorter than go RT (see Table 1). This prediction held for all stop tasks, *F*s > 4.5, *p*s < .05. Importantly, stopping latencies showed an orderly pattern between Tasks, $F(2, 30) = 19.9$, $p < .001$. SSRT

[1] It has been argued that a comparison between conditions with an unequal amount of trials in conditions can distort RT estimates when medians are used (Miller, 1988). The reported effects, however, did not change when means were analyzed instead of median RT values.

was longest in the Stop-b task (260 ms) and shortest in the Stop-a task (221 ms) with intermediate values (240 ms) in the Stop-c task (*p*s < .01). This pattern is similar to that observed in studies comparing response latencies on a-, b-, and c-reaction tasks. Applying Donders' subtraction method reveals a signal-discrimination stage of approximately 19 ms (SSRT Stop-c minus SSRT Stop-a). The response-mapping stage was estimated around 20 ms (SSRT Stop-b minus SSRT Stop-c).

Invalid Stop Trials

The lower panel of Table 1 presents results obtained on invalid stop trials requiring an overt response. The percentage of response omissions on invalid stop trials was low (< 2.3%) but higher in the Stop-b than in the Stop-c task, $F(1, 15) = 8.61$, $p = .01$. Responses on invalid stop trials were substantially delayed compared to responses on go trials (*p*s < .001) and are slower in the Stop-b than in the Stop-c task, respectively, 558 versus 481 ms, $F(1, 15) = 6.97$, $p = .02$. A possible explanation for this slowing of responses on invalid stop trials may be that the go response was initially inhibited and then re-initiated after correctly classifying the signal as invalid (Coxon et al., 2007). In this respect, the obtained invalid RT is an overestimation of the actual processing time of the invalid stop signal since it consists of two classes of responses, that is, slow responses on which the stop signal is totally processed and classified as invalid versus fast responses on which the response was too fast to classify the stop signal. To test this hypothesis, the finishing time of the stop process (i.e., the *n*th percentile of the go RT distribution, see Data Analysis section) was used and set as cut-off point for the invalid-RT distribution. This yielded a class of invalid RTs that were shorter than the finish time (n) and a class of invalid RTs that were longer. Median RTs for fast and slow invalid responses were computed individually and entered into ANOVA. The ANOVA revealed that fast invalid responses did not differentiate between tasks ($F < 1$), pointing to a similar class of fast responses that win the race against invalid stop-signal processing. In contrast, slow responses on invalid stop trials did differentiate between selective stop tasks: slow invalid Stop-b responses were prolonged compared to slow invalid Stop-c responses, respectively, 654 versus 551 ms, $p < .001$.

Design Issues

Application of Donders' subtraction method to the stopping latencies that emerged from this experiment yielded an interpretable decomposition of stages comprised by the processing of the stop signal. It should be noted, however, that a design issue could well have differentially affected stopping latencies. Recall that the proportion of non-signal trials (go trials) was 82% in the global task whereas it was 65% in both selective tasks. This was done to keep the proportion of valid stop-signal trials (18%) equal across tasks. This may have induced a bias toward adopting a response strategy that emphasized speed over inhibition in the Stop-a task (Logan, Cowan, & Davis, 1984). This notion is supported by the observation that go responses were faster in the global Stop-a task than in the selective stop tasks. To test the implication of these probability differences on SSRT, Experiment 2 presented an equal percentage of go trials (i.e., 65%) across stop tasks. In addition, a Choice-RT task without stop signals was included to quantify the slowing of responses when stop signals are occasionally presented. We hypothesized that increasing the number of stop trials would not affect global stopping latency (Ramautar, Kok, & Ridderinkhof, 2004). A subsequent goal of Experiment 2 was to test the robustness of selective stopping latencies reported in Experiment 1.

Experiment 2

Method

Participants

A total of 16 undergraduate students (9 women, *M* age = 21.4, *SD* = 2.1 years) from the University of Amsterdam participated in this study for course credits. All had normal or corrected-to-normal vision and two participants were left-handed. None participated in Experiment 1.

Material, Stimuli, and Procedure

Choice-RT Task

The Choice-RT task consisted of go signals only, stop signals were not included. The participants were instructed to press the left key with the left index finger and the right key with the right index finger to white arrows pointing left and right, respectively. The Choice-RT task consisted of one experimental block of 100 trials with equal numbers of right- and left-pointing arrows that were varied randomly within a block.

Stop-a Task

A stop signal occurred on 35% of the trials (65% go trials), instructing the participant to refrain from responding to the arrow. Half of the participants were presented with 35% blue stop signals only while the other half received 35% pink stop signals. The Stop-a task consisted of five experimental blocks with 100 trials each.

Stop-b and Stop-c Tasks

Materials, stimuli, and procedure of the Stop-b and Stop-c tasks were identical to those used in Experiment 1 and contained a color change in 35% of the trials (18% were valid and 17% invalid stop trials) and 65% go trials. The valid stop-signal color in the Stop-c task equaled the stop color presented in the Stop-a task. Participants performed 10 experimental blocks of 100 trials.

Procedure

The four tasks were administered during two separate sessions on different days that were scheduled within five days. Each session started with the Choice-RT task followed by one of the stop tasks. The order of the three stop tasks was counterbalanced across participants. To rule out differences in task performance over time, the Stop-a task was split over sessions, that is, three experimental blocks in one session and two in the other session. Practice procedures and block duration were similar to Experiment 1.

Results and Discussion

Data analysis was similar to Experiment 1. An initial comparison between sessions (with Session, one versus two, as an extra factor) revealed that participants responded faster to go signals on the Choice-RT task in the second compared to the first session, $F(1, 15) = 39.2$, $p < .001$. Most importantly, the analysis of global SSRT yielded no difference between session one and two with SSRTs of, respectively, 211 versus 213 ms ($F < 1$). Thus, data were collapsed across sessions for subsequent analyses.

Response Execution

The go results for each task are presented in the upper panel of Table 2. Percentages of errors and omissions were low (i.e., below 3%) indicating that go responses were highly accurate. Analysis of RT yielded a significant main effect of Task, $F(3, 45) = 5.2$, $p = .004$. Pairwise comparisons indicated that participants responded faster on the Choice-RT task compared to the stop tasks ($p = .008$). The insertion of stop signals apparently delayed responding to go arrows despite task instructions and the use of a tracking algorithm. In contrast to Experiment 1, participants responded slower on go trials in the Stop-a task compared to the selective stop tasks (ps < .04). The prolonged go RT in the Stop-a task is likely due to the smaller proportion of trials requiring a motor response. In the Stop-a task, 65% of the trials required an overt response whereas in both selective tasks, 82% required a button-press response, as these tasks include 65% go trials and 17% invalid stop trials.

Response Inhibition

Valid Stop Trials

Table 2 presents the valid and invalid stop results. The tracking algorithm targeted inhibition rates that were close to 50% for all three stop tasks. However, the Stop-b task showed a somewhat higher stop-respond percentage than the Stop-c and Stop-a tasks (ps < .02) (overall $F(2, 30) = 14.52$, $p < .001$). The race model predicts that the RT on stop-respond trials is shorter than on go trials without a stop signal. This prediction was supported by the data from the Stop-a task, $F(1, 15) = 60.6$, $p < .001$. For the Stop-b and Stop-c tasks, however, stop-respond RT did not differ from RT on go trials (ps > .10). Importantly, SSRT discriminated between stop tasks, $F(2, 30) = 48.24$, $p < .001$. Like in Experiment 1, selective stopping took significantly more time in the Stop-b task compared to the

Table 2. Percentages of choice and omission errors, median RT on go trials for Sessions 1 and 2, and averaged over Sessions, and stop-respond (in %), stop-respond RT, stop-signal delay, and stop-signal RT (SSRT) on valid stop signals, and omissions (in %) and fast and slow invalid RT on invalid stop trials per task in Experiment 2 (*SD* between parentheses)

	Task			
	Choice-RT	Stop-a	Stop-b	Stop-c
Go trials				
% Choice errors	2.8 (2.4)	1.3 (2.0)	1.0 (1.4)	1.7 (1.5)
% Omissions	0 (0)	0.4 (0.6)	0.8 (1.1)	0.4 (0.6)
Go RT Session 1	355 (28)	365 (27)	342 (20)	347 (12)
Go RT Session 2	328 (27)	359 (30)	360 (17)	348 (11)
Go RT over Sessions	340 (25)	361 (26)	351 (21)	347 (11)
Valid stop trials				
% Stop-respond	–	50.1 (1.7)	53.9 (3.1)	51.7 (1.9)
Stop-respond RT	–	338 (64)	361 (91)	343 (60)
Stop-signal delay	–	151 (35)	90 (31)	105 (22)
SSRT	–	210 (20)	265 (31)	244 (23)
Invalid stop trials				
% Omissions	–	–	5.9 (8.0)	1.8 (1.7)
Invalid RT	–	–	458 (143)	405 (99)
Fast invalid RT	–	–	321 (27)	320 (24)
Slow invalid RT	–	–	529 (129)	453 (84)

Stop-c task (265 vs. 244 ms, $p = .003$). Moreover, selectively inhibiting a motor response in the Stop-c task was delayed 34 ms compared to global inhibition in the Stop-a task (210 ms, $p < .001$). Donders' subtraction method estimates the signal-discrimination stage of the inhibition process of approximately 34 ms (i.e., SSRT in the Stop-c task minus SSRT in the Stop-a task). The response-mapping stage was estimated to take about 21 ms (i.e., SSRT in the Stop-b task minus SSRT in the Stop-c task). Thus, Experiments 1 and 2 revealed similar Stop-b SSRT (respectively, 265 and 260 ms) and Stop-c SSRT (respectively, 244 and 240 ms) (between-subjects ANOVAs, $F < 1$).

Invalid Stop Trials

Analysis of omission errors on invalid stop trials again revealed increased response omissions in the Stop-b task (5.9%) than in the Stop-c task (1.8%), $F(1, 15) = 8.46$, $p = .01$. Like in Experiment 1, RT on invalid stop trials was considerably slower than RT on go signals (*p*s < .001, see Table 2) and invalid responses again were slower in the Stop-b than in the Stop-c task, respectively, 458 versus 405 ms, $F(1, 15) = 7.4$, $p = .02$. Analyses of slow versus fast responses on invalid stop trials yielded a similar pattern as in Experiment 1. Fast invalid responses did not differentiate between the Stop-b and Stop-c tasks (321 vs. 320 ms, $F < 1$), whereas slow invalid responses were substantially prolonged in Stop-b compared to the Stop-c task, respectively, 529 versus 453 ms, $F(1, 15) = 19.5$, $p = .001$.

Comparing Experiments 1 and 2

Experiments 1 and 2 yielded highly similar patterns. Specifically, selective SSRT was around 260 ms for the Stop-b task and about 240 ms for the Stop-c task. In contrast to Experiment 1, stop-respond RT in the selective stop tasks was not significantly shorter than go RT in Experiment 2. This might point to a violation of the race model's assumption of independence (Logan & Cowan, 1984). However, selective SSRTs in Experiment 2 were virtually identical to the values obtained in Experiment 1. Hence, possible violations of the race model did not bias estimation of selective stopping latencies in Experiment 2. Based on the obtained SSRT values, estimates of the processing time to map the stop color to the response hand were about 20 ms for both Experiments. Global stopping turned out to be slightly, albeit not significantly, faster in Experiment 2 compared to Experiment 1 (210 vs. 221 ms, $p = .19$). The estimated signal-discrimination stage therefore was somewhat longer in Experiment 2 than in Experiment 1 (34 vs. 19 ms). In the following, two possible explanations for this disparate global SSRT finding will be discussed further. First, the two global stop tasks differed in the percentages of stop trials. The Stop-a task in Experiment 1 contained 82% go and 18% stop signals. Decreasing the number of go trials to 65% and increasing stop-signal percentage to 35% in Experiment 2 may have caused the somewhat shorter global SSRT. Second, recall that in Experiment 1, participants stopped globally to blue and pink signals, whereas participants saw only one stop color in Experiment 2. A possible task order effect in Experiment 1 may have occurred for a subset of participants who performed the selective Stop-c task before doing the global Stop-a task. Consider for example, those who performed the selective task first, responding to (invalid) blue signals and stopping to (valid) pink stop signals. Subsequently, they were presented with the same two stop colors in the global stop task, the color associations established in the previous selective task (i.e., blue = respond, pink = stop) might have prolonged global SSRT to blue signals relative to pink signals. This hypothesis was formally tested using the Stop-a data obtained in Experiment 1. First, an ANOVA performed on the group of participants that performed Stop-a after Stop-c ($n = 8$) confirmed that global stopping to the color that was invalid in Stop-c was considerably prolonged compared to global stopping to a previously valid stop color, respectively, 232 versus 215 ms, $F(1, 7) = 9.06$, $p = .02$. In contrast, for those participants who did the Stop-a first ($n = 5$) global SSRTs to stop colors designated later in the selective Stop-c task as valid and invalid signals were 213 and 217 ms (respectively) and did not significantly differentiate ($F(1, 4) = 1.0$, $p = .37$).

Apparently, task order effects for a subset of participants slightly increased global SSRT in Experiment 1 compared to Experiment 2. Thus, the estimated signal-discrimination stage of 34 ms in Experiment 2 may be a better representation of what should be the color-discrimination stage. To assess the two issues in more detail, Experiment 3 was designed to systematically quantify both the effect of stop-signal probability (18% vs. 35%) and of the number of stop-signal colors (one vs. two) on global stopping latency.

Experiment 3

Method

Participants

Seventeen, right-handed, undergraduate students (10 women, $M = 19.3$, $SD = 1.8$ years) participated in Experiment 3 for course credits. None of them participated in any of the previous experiments.

Material, Stimuli, and Procedure

Participants performed on three global stop task versions; one version was almost identical to the Stop-a task presented in Experiment 1 and contained 82% go trials and 18% stop signals, with both pink (9%) and blue (9%) stop colors intermixed in a block of trials. However, two tracking algorithms adjusted stop-signal delay separately for blue and pink stop signals. Participants performed on six experimental blocks to obtain enough trials to compute SSRT to pink and blue signals separately. A second global stop task was identical to the one presented in Experiment 2, containing 65% go trials and 35% stop signals and just one stop color. Half of the participants received blue stops while the other half were presented with pink stop signals only. Three experimental blocks were administered containing 100 trials each. Third, a new Stop-a task was introduced that contained 65% go trials and 35% stop signals, but now with both pink (18%) and blue (17%) stop colors were equiprobable within in a block of trials. Again, stop-signal delay was controlled for blue and pink stop signals separately. Three blocks of trials were presented. Instructions were similar across tasks, that is, participants had to refrain from responding whenever a stop signal appeared, irrespective of stop color.

Data Analysis

One participant did not perform all tasks and was therefore excluded from the analysis leaving a total of 16. Calculation of error percentages and latency measures followed those of the previous Experiments. For the two tasks that presented both blue and pink stop signals within a block of trials, SSRT was computed separately for each stop color and an additional repeated-measures ANOVA was performed on SSRT with Stop color (pink vs. blue) as within-subject factor.

Results and Discussion

Response Execution

Again, error and omission percentages were below 1% for all tasks (see upper panel of Table 3). A significant main effect of Task on go RT was obtained, $F(2, 30) = 6.88$, $p = .008$. As predicted, responses on go trials were slower if the proportion of go signals was lower (65%) compared to when go signals were more frequent (82%). Conversely, participants slowed their response speed when stop signals were presented more frequently.

Response Inhibition

Stop-respond proportions were around 50% and did not differentiate between the three global stop tasks, $F(2, 30) = 2.49$, $p = .10$. Stop-respond RT was shorter than go RT for all Stop-a tasks in the present experiment, Fs > 61.32, ps < .001. Within-subject analysis of stopping latency revealed that the color of the stop signal (blue vs. pink) did not affect SSRT (Fs < 1.85, ps > .19). Subsequent between-subject comparisons showed that SSRT did not discriminate between participants stopping to blue signals and those stopping to pink stop signals (respectively, 212 vs. 201 ms, $p = .28$). SSRT to blue and pink signals were therefore averaged to obtain a single global SSRT for each of the three tasks. Importantly, the ANOVA on the global SSRT did not differ between Tasks, $F(2, 30) = 1.92$, $p = .17$. That is, presentation of two stop colors compared to the presentation of just one stop color did not affect global stopping (ps > .23). In addition, the task with 18% stop signals yielded an SSRT (213 ms) that was very similar in magnitude as in the two stop tasks that employed 35% stop signals (SSRT of 204 ms for stopping to two stop colors and SSRT of 207 ms for stopping to one color, ps > .11). The absence of stop-signal probability effects on SSRT is in accordance with previous studies (e.g., Ramautar et al., 2004).

In sum, the results of Experiment 3 clearly indicate that global stopping was not affected by stop-signal probability or by the use of different stop-signal colors.

General Discussion

This study examined the processing of global and selective stop signals and was inspired by the reasoning that the architecture of the stop process – like that of the go process – involves distinct processing stages. Using Donders' subtraction technique we were able to isolate the latencies of two substages of stop-signal processing; namely the duration

Table 3. Percentages of choice and omission errors and median RT on go trials and percentage of stop-respond trials, stop-respond RT, stop-signal delay, stop-signal RT (SSRT) to pink and blue stop signals, and average SSRT (over SSRT pink and SSRT blue) in Experiment 3 (*SD* between parentheses)

	Stop-a task		
	1 Stop color, 35%	2 Stop colors, 35%	2 Stop colors, 18%
Go trials			
% Choice errors	0.4 (0.6)	0.7 (1.1)	0.9 (0.9)
% Omissions	0.2 (0.3)	0.2 (0.3)	0.7 (2.1)
Go RT	411 (81)	399 (75)	378 (69)
Stop Trials			
% Stop-respond	50.1 (1.8)	48.3 (2.8)	49.1 (2.8)
Stop-respond RT	373 (65)	405 (113)	385 (80)
Stop-signal delay	203 (41)	191 (41)	163 (36)
SSRT pink	201 (19)*	203 (14)	210 (21)
SSRT blue	212 (21)*	205 (17)	215 (23)
Average SSRT	207 (20)	204 (14)	213 (20)

*Between-subject manipulation.

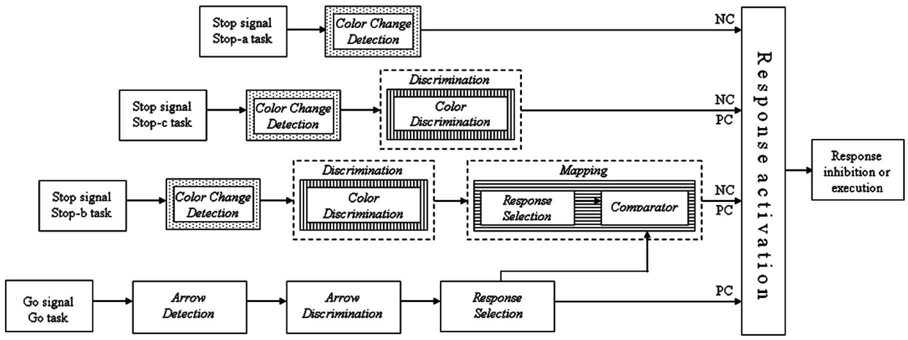

Figure 2. Model of stages of go (bottom series) and stop-signal processing in the Stop-a, Stop-b, and Stop-c tasks. Separable components in Stop-a are illustrated by dots, by vertical line texture in Stop-c, and by horizontal line texture in the Stop-b task. NC and PC stand for negative or positive call, respectively. Note that PC on invalid stop trials may include an additional re-initiation stage (not shown).

of 34 ms for stop-signal discrimination and 20 ms for the mapping stage of the stop process.

Global inhibition required participants to stop a motor response as soon as they detected the stop signal (Stop-a task). All three experiments showed global stopping latencies in the range of 210 ms even though stop-signal probability and different stop colors were varied between and within experiments. The value closely approaches latencies reported in various other stop studies although different go tasks, stop-signal probabilities, and stop-signal intensities were used between reported studies (see Introduction for relevant references). This supports the notion that global SSRT is rather constant across design manipulations (see also Logan, 1994). Selective inhibition required discrimination between visual stop stimuli in the Stop-c task (e.g., stopping to a blue but not to a pink signal). The Stop-b task added the requirement to map the outcome of the stop-signal discrimination process onto the response required by the go signal. Consequently, stopping was prolonged due to the insertion of an additional discrimination stage (in Stop-c) and an additional mapping stage (in Stop-b). In both Experiments 1 and 2, selective stopping in the Stop-b tasks (around 264 ms) was significantly delayed compared to selective stopping in the Stop-c tasks (around 244 ms). This latter finding indicates that the need to map the outcome of the stimulus discrimination process onto the responding hand yields an additional delay in SSRT. If the assumptions of Donders' subtraction method are valid (Donders, 1868/1969; Gottsdanker & Shragg, 1985; Ulrich et al., 1999; van der Molen et al., 1991), the current results provide latency estimates of the stimulus-discrimination and mapping stages of the stop process. Thus, subtracting Stop-a from Stop-c stopping latency yields an estimated duration of 34 ms for the stop-signal-discrimination stage of the inhibition process. Likewise, subtracting Stop-c from Stop-b stopping latency results in an estimated duration of about 20 ms for the mapping stage of the stop process.

The present findings provide a first step toward identifying which processing components do and which do not affect the inhibition process. Apparently, stop probability does not affect global SSRT, nor does the number of different stop signals that are included. It is when the discrimination of stop signals becomes relevant for inhibition that SSRT is prolonged (Stop-c) or when the decision to stop depends on a mapping stage (Stop-b). Figure 2 presents a conceptualization of the information flow through go and stop stages. On go trials, the arrow is presented to a stimulus-detection stage and the output of this stage is fed into the stimulus-discrimination stage and this output then enters into the response-selection stage in which the arrow direction is mapped onto the appropriate response. The output of the response-selection stage is fed into the response-activation stage and the response is executed when response activation reaches a certain threshold. On stop trials, the processing of the go stimulus is identical to the processing of the go stimulus on go trials until interruption by processing of the stop stimulus. In the Stop-a task, the presence of a stop signal is detected (i.e., the color change of the arrow) and the output of this stage makes a negative call to the response-activation stage, resulting in response inhibition. In the Stop-c task, the output of the stop-stimulus-detection stage feeds into a color-discrimination stage and depending upon its output, a positive or negative call is made to the response-activation stage resulting in, respectively, response execution or inhibition. The information flow in the Stop-b task is more complex. In this task, the processing of the stop signal includes a response-selection stage in which the color of the arrow is mapped onto the appropriate hand. The output of this stage enters a comparator stage that matches this output against the output of the response-selection stage of go-signal processing. In case of a match, the comparator stage makes a negative call to the response-activation stage of go-signal processing resulting in response inhibition. If the outputs of the response-selection stages differ, the comparator stage makes a positive call to the response-activation stage resulting in response execution. This conceptualization is consistent with the observed SSRTs across tasks. The relatively prolonged RTs on invalid stop trials probably relate to the occasional initial inhibition (i.e., a negative call) that may be issued during early stop-signal processing. After classifying the signal as invalid, this initial negative call is then followed by a re-initiation of the go response (i.e., a positive call). This implies that on a subset of invalid trials, stop-signal processing includes the discrimination stage (and mapping stage in the Stop-b task), but also contains a re-initiation stage (van den Wildenberg & van der Molen, 2004a).

At this point, it could be argued that the current findings may not be compatible with the independence assumption that underlies the race model (Logan & Cowan, 1984). First, adding stop signals into the design lengthened go RT compared to RT in a task with only go trials (Choice-RT task, Experiment 2), a typical observation in the stop-signal literature (e.g., van den Wildenberg & van der Molen, 2004a; Verbruggen et al., 2006, see Verbruggen and Logan, 2009 for a discussion of proactive response strategies in the stop task). Apparently, the latency of go-signal processing was affected by the presence of stop-signal processing, which points to a violation of what has been coined "functional" or "context" independence (e.g., Band et al., 2003; Ridderinkhof et al., 1999). Although simulation studies by Band et al. (2003) showed that the race model yields reliable estimates of SSRT despite context dependence between stopping and going (cf., Ridderinkhof et al., 1999) meeting the premise of "stochastic" independence seems more critical (Logan, 1994; Logan & Cowan, 1984). Stochastic independence refers to the condition that stopping and going are not correlated (i.e., go RT and SSRT are independent random variables). The current conceptualization of information processing in the Stop-b task seems clearly at odds with the stochastic independence assumption, as stop-signal processing depends on the go process. The question then is whether a violation of stochastic independence invalidates calculation of Stop-b SSRT using the race model. Again, extensive simulation studies performed by Band et al. (2003) demonstrated that the race model is quite robust, even against violations of stochastic independence. These simulations indicated that a positive correlation between stopping and going yielded a lengthening of SSRT with stop-signal delay (Band et al.; see also de Jong, Coles, Logan, & Gratton, 1990) but reliable SSRTs were nonetheless obtained when using a tracking algorithm similar to the one in the present study.

Recently, an extension of the classical race model was formulated, called the interactive race model which is based on theoretical and empirical stop data obtained from saccadic eye movements (Boucher, Palmeri, Logan, & Schall, 2007). Here too stopping is conceptualized as a multistage process. Initial encoding stages during which the go and stop processes do not interact are followed by a brief interruption stage during which the stop unit inhibits the go unit. In this sense, successful inhibition in the Stop-b and Stop-c tasks depends then on reaching the interruption stage later in time while stopping may be exerted by a similar stop mechanism as in the Stop-a task. The current study interpreted SSRT lengthening under selective stopping instructions as a consequence of additional stop-signal processing stages (as depicted in Figure 1). Although discriminating between stop signals or mapping inhibition on a response prolonged selective SSRT, the inhibition mechanism itself might be the same across stopping conditions (see also Coxon, Stinear, & Byblow, 2006). Alternatively, it could be argued that this lengthening is due to the engagement of a selective but slower inhibition mechanism that is different from global inhibition, which renders an explanation in terms of additional stages invalid. A recent study, differentiating global versus selective stopping, used simultaneous right- and left-hand responses on go trials (Aron & Verbruggen, 2008). A selective stop signal instructed participants to inhibit either the left- or the right-hand press. If subjects did not know in advance which hand they were signaled to stop, selective SSRT equaled global SSRT. However, if a cue was presented like "maybe stop right", selective stopping latency was prolonged. Apparently this foreknowledge afforded slower selective inhibition, while fast global inhibition was engaged when it is important to stop quickly. While selective stopping was prolonged at the behavioral level, it remains unclear whether implementation of the final stage of response inhibition was different between global and selective stopping (see also Aron & Verbruggen, 2008; Coxon et al., 2006).

In closing, the orderly stop latency patterns reported in the present study demonstrate that Donders' subtraction method provides an informative tool to dissect stop-signal processing into more basic subcomponents. Future electrophysiological studies may link particular substages of selective inhibitory processing with distinct neural markers, addressing the question whether global and selective stopping rely on a single or on distinct neurophysiological mechanisms (e.g., de Jong, Coles, & Logan, 1995; van Boxtel et al., 2001).

Acknowledgments

This study was supported by NWO grants to MvdM and WPMvdW (MaGW Grant 400-03-261 and VENI Grant 451-06-012, respectively). Adinda Post Uiterweer is gratefully acknowledged for her help in collecting part of the data and we thank Borís Burle for helpful discussions. Further thanks go to Bert van Beek for his help in programming the computer tasks and to Marcus Spaan and Bert Molenkamp for technical support. We are indebted to Frederick Verbruggen and Martina Rieger for constructive comments on a previous version of this article.

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Received July 3, 2008
Revision received March 21, 2009
Accepted March 22, 2009
Published online: November 6, 2009

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