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

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8.1 Summary

This thesis is concerned with the inhibition of motor responses in the stop-signal paradigm. It centers on stopping, that is the internal cognitive response that is initiated by the onset of a stop signal and ends with the actual interruption of the motor response. A *horse-race model* provides an accurate description of the behavioral data observed in the stop task. One of the virtues of the race model, as formulated by Logan and Cowan (1984), is that, based on few formal assumptions, it allows for calculating the latency of the covert stop processes, that is, *stop-signal reaction time* (SSRT). The goal was to look beyond SSRT as a descriptive measure of stop performance and to learn about the nature of the stop process. In pursuit of this goal, several perspectives taken from the experimental psychological framework were adopted.

8.1.1 *Interaction patterns of stopping and reactive inhibition*

One such perspective is covered in Chapter 2, and involves the factorial combination of stopping with other types of behavioral inhibition. Stop-signal inhibition was compared in conditions which either do or do not require some other form of inhibition. The potential interest of the analysis of resulting interaction patterns has been expressed by Logan (1994, p. 192). He theorized that stopping a response might be easier if the primary task itself draws upon some form of inhibitory process as well. Alternatively stopping a response that requires inhibition itself might be harder if the stop process as well as the go process depend on a limited capacity for inhibition. It has been suggested that the interaction between tonic inhibitory control of response readiness and phasic inhibitory control of an imminent response is of considerable interest (cf. De Jong, Coles, & Logan, 1995, p. 507). Chapter 2 presented the first attempt at a systematic assessment of this issue.

This study addressed the issue whether reduced response readiness, or inhibitory state, affects SSRT. In this study, participants were presented with various letters and were required to distinguish between consonants and vowels. In some instances an X was presented to indicate that a nogo trial was imminent. The placement of these Xs within a series of trials created inhibitory episodes because subjects delayed choice reactions on go trials while awaiting an upcoming nogo trial compared to control sequences. Most importantly, stop reactions were delayed, not facilitated, during test episodes compared to control episodes. This observed interaction pattern indicates that a state of reduced readiness has similar effects on both go processing and stopping by slowing them both.

This finding might be taken to mean that both stop-signal inhibition and reactive inhibition associated with the primary task compete for the same resources. However, in Chapter 2 we proposed an alternative explanation. It is hypothesized that subjects adopted a lower motor readiness during the inhibitory phase to avoid errors of commission to the anticipated nogo signal. Consequently a larger and more time-consuming increment is needed to overcome the

motor limit when a go response is called for. It is conjectured that reduced readiness gives rise to more forceful responses which are then more difficult to inhibit.

8.1.2 Relating stop latency to response force: A physiological perspective

The study described in Chapter 3 was carried out to test directly the hypothesis formulated in Chapter 2 that the duration of the stop-signal process is longer for forceful than for less forceful responses. Subjects completed a simple reaction time (RT) task, a choice RT task, and two go/nogo tasks with 80% and 50% response probabilities, respectively. The task set was administered under two conditions: A condition in which the imperative response signal could be followed occasionally by a stop signal (the stop-signal paradigm), and a control condition without stop signals (the standard Donders paradigm). Response force was recorded with force transducers. Based on the results reported in Chapter 2, and the results on response force reported by Mattes, Ulrich, and Miller (1997) and by Ulrich, Mattes, and Miller (1999), we expected more forceful responses and, consequently, longer stop latencies in the go/nogo tasks than in the simple and choice RT tasks. We successfully replicated and also extended the results of Chapter 2 on response force and RT. The results confirmed the hypothesis that stopping is more difficult when response readiness is low than when it is high.

8.1.3 Fractionation of simple and selective stopping: A developmental perspective

Another approach examining the nature of inhibitory processing has been adopted in Chapter 4. This approach concerns the developmental perspective. Previous researchers using the standard stop-signal paradigm have suggested that simple stopping, that is the inhibition of whatever response is ongoing, improves during early childhood and declines during later adulthood (Williams, Ponesse, Schachar, Logan, Tannock, 1999). Recently, Bedard et al. (2002) have extended these findings by examining age-related change in selective inhibitory control. Their selective inhibition task focused on the perceptual end of stop-signal processing and required their subjects to distinguish between two auditory signals. Subjects were instructed to inhibit the planned response in the event of the presentation of one tone (designated as the valid stop signal) but not in the event of another tone (an invalid stop signal).

The first aim of the study reported in Chapter 4 was to investigate age-related changes throughout childhood in the motor end of selective inhibitory processing and to contrast the developmental trend in selective stopping with age-related changes in both simple (or global) stopping and response execution. To this end, we assessed the speed of response execution and speed of inhibition in three age groups (7-year-olds, 10-year-olds, and young adults) in a choice RT task, a simple stop task, and a selective stop task. The second aim was to investigate whether the speed of selective inhibition is determined by the response that the subject had to stop. Response selection demands were manipulated by varying spatial stimulus-response compatibility (SRC) to the go signal in all three tasks. In the choice RT task, the 7-year-olds responded slower and made more errors than the subjects in the other two groups (these groups did not differ). RT differences between incompatible and compatible responses in the choice RT task were larger in the 7-year-olds compared to the subjects in the two older groups.

In the simple stop task, 7-year-olds were slower in response execution and in inhibition to stop signals compared to the older groups. In addition, this group committed significantly more errors than the two older groups. SRC did not affect go-signal RT, error rates, and stop latencies. Young adults were able to selectively stop their responses more quickly compared to 10-year-olds, and 10-year-olds in turn were faster than the 7-year-olds. In all age groups, compatible responses were selectively stopped more quickly than incompatible responses. The 7-year-olds displayed the greatest slowing of incompatible stopping.

These findings were interpreted to indicate that SRC influenced the speed of response execution, but that SRC effects decreased with increasing age, and SRC effects disappeared when including a demand for inhibition increased task demands. In addition, SRC influenced selective but not simple inhibition. Most importantly, simple and selective inhibition improved throughout childhood, but at different rates, with selective inhibition showing the most pronounced change. It was suggested that the greater number of cognitive control processes required in the selective stop tasks may have contributed to this more pronounced developmental trend.

8.1.4 Stopping is a response: An information-processing perspective

In Chapters 5 and 6 the proposition is tested that stop processes are quite similar in nature to go processes. Go signals require perceptual discrimination, translation into a correct action, and the subsequent programming and execution of that action. Likewise, stop signals are considered to require perceptual discrimination, translation into an appropriate action (i.e., inhibition of ongoing responses), and then the programming and execution of the inhibitory response. The stop-signal paradigm was combined with the additive factors method (AFM, in Chapter 5) and the Simon task (Chapter 6), which represent two paradigms that have advanced our understanding of go-signal processing.

The main aim of the experiment described in Chapter 5 was to identify stages in the stop process, extending from stop-signal presentation to the actual inhibition of the prepotent motor response. The AFM paradigm was used to achieve this aim. First, a standard AFM design was used to obtain additive effects of signal discriminability (high vs. less) and SRC (compatible vs. incompatible) on separate stages of the go-reaction process. Analyses of the additive interaction pattern of main effects on go-signal RT obtained in the standard AFM tasks confirmed the independent effects on the perceptual stage and response-related stages of signal discriminability and SRC, respectively.

To replicate this pattern on SSRT, the go signals that were used in the standard AFM tasks then served as stop signals in the selective stop tasks. Participants were instructed to distinguish between two visual stop signals, and to inhibit their primary-task response upon the presentation of one stop signal and not the other. In the compatible stop conditions, subjects had to stop only if the location of the stop signal was compatible with respect to the response location associated with the go task (e.g., a left hand response should be inhibited if a stop signal is presented to the left). Alternatively, the incompatible stop instruction required subjects to inhibit the go response if the stop signal appeared in the direction opposite to the response hand indicated by the go signal (e.g., a left-hand response should be inhibited if a stop signal is presented to the right).

Analyses of stop latencies showed that selective stopping to incompatible stop signals was slower than stopping to compatible stop signals (e.g., Van den Wildenberg & van der Molen, 2003a). Contrary to predictions, stop-signal discriminability did not systematically affect selective stop speed: selective stopping to easily distinguishable stop signals was as fast as stopping to less distinguishable stop signals. Based on the obtained SSRT pattern it was inferred that the current levels of discrimination did not effectively affect stop speed, possibly because less distinguishable stop signals were not that hard to discriminate. This conjecture was confirmed by follow-up analysis on a subset of subjects selected on the basis of a relatively large effect of signal discriminability in the standard AFM tasks. SSRTs obtained from this subset showed the anticipated effects of stop-signal discriminability and compatible stopping tended to be faster than incompatible stopping. Moreover, these main effects proved to be additive with respect to SSRT. This pattern indicated that, at least in a subset of participants, signal discriminability and SRC affected two stages of stop-signal processing independently. In conclusion, the obtained additive relation between (stop-) signal discriminability and (stop-) SRC on stop latency confirmed the idea that the stop process was successfully decomposed into two distinct stop-signal processing stages.

Chapter 6 combined the stop-signal task with the active suppression of response activation that is related to irrelevant aspects of imperative signals as used in the Simon task. Stimuli in the Simon task contain an irrelevant aspect (the location of the signal relative to a fixation point, left or right) as well as task-relevant information (such as the color of the signal which informs the subject to respond with the right or left hand). Congruent trials are defined as those trials on which the irrelevant and the relevant information coincide (e.g., the color signals a right-hand response, and is presented to the right of a fixation point). These congruent trials are associated with faster responses. Alternatively, on incongruent trials the relevant and irrelevant stimuli aspects do not correspond (e.g., the color signals a right-hand response, and is presented to the left of a fixation point). Responses to incongruent trials are usually slower. Response activation processes are described by a dual-process model (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). The response activation that is triggered by the irrelevant signal attribute is actively suppressed by the subject, according to the activation-suppression hypothesis (Ridderinkhof, 2002a). This suppression needs some time to build up and is predicted to be more effective, resulting in a diminished Simon effect when the relevant information is processed relatively late (e.g., when the color of the signal is harder to distinguish). The results that we obtained using a standard Simon task are in accord with these models. Responses to hard-to-discriminate signals (yellowish-green vs. greenish yellow) were slower than responses to easy-to-discriminate signals (blue vs. red), and responses to incongruent signals were found to be slower than to congruent signals and. Moreover, the Simon effect was attenuated in the blocks with harder-to-discriminate stop signals, which confirms the assumption that active suppression of irrelevant location information needs time to build up and become more effective.

To investigate whether the processing of relevant and irrelevant aspects of stop signals can be interpreted in terms of the dual-process model, the Simon stimuli were used as stop signals in a simple stop task and in two selective stop tasks. Selective stop latencies were longer than simple stop latencies (Van den Wildenberg & van der Molen, 2003a). In addition, selective stopping to harder-to-discriminate stop signals was slower than selective stopping to easy-to-discriminate stop signals. We also observed Simon effects on stop latency. Simple

stopping was enhanced given spatially congruent stop signals. Finally, we observed a zero congruency effect with hard-to-discriminate stop signals, and a non-zero congruency effect on selective SSRT with easy-to-discriminate stop signals. Apparently, with longer stop latencies, the processing of the relevant aspect of the stop signal (color) was not affected by the irrelevant location of the stop signal.

8.1.5 *The basal ganglia and stopping: A neurophysiological perspective*

Chapter 7 adopted the neurophysiological perspective to explore the nature of inhibitory motor control vis-à-vis basal ganglia functioning. This investigation was inspired by Brunia (1993) who suggested that a direct connection from the prefrontal cortex to the *nucleus reticularis* (RN) might be a possible route via which response inhibition could be realized. Given the anatomical constraints of this nucleus, it is difficult to present experimental evidence for that idea. Some years ago he proposed an alternative stop route, that is the excitatory pathway from the cortex to the *subthalamic nucleus* (STN; Brunia, personal communication). Activation of this pathway results in a blocking of thalamo-cortical output, which itself is considered a necessary condition for movement production. Although most neurophysiological investigations on inhibitory motor control focused on the involvement of frontal brain areas (see Band & van Boxtel, 1999 for a review), for practical reasons few experiments have directly investigated the role of the basal ganglia in inhibitory motor control. Recently techniques have been developed to intervene in basal ganglia functioning by means of deep brain stimulation (DBS). Two groups of patients who were treated with DBS participated in this study. The members of one group had a neurostimulator implanted in the STN to reduce the symptoms of advanced stages of Parkinson's disease. In a second group of patients diagnosed with Parkinson's or Minor disease, the electrode targeted the ventral intermedius nucleus (Vim) of the thalamus to treat severe (essential) tremor. Participants performed twice a stop-signal task and a go/nogo task - once with the neurostimulator turned on, and once with the stimulator off - during alternate runs in one session. Results obtained from the go/nogo task indicated that neurostimulation did not change speeded performance or accuracy in both patient groups. In the stop task, results indicated that DBS of the thalamus did not systematically affect task performance. In contrast, stimulation of the STN significantly facilitated response execution as well as stop processes. These results were interpreted in terms of candidate neural circuits underlying inhibitory motor control.

8.2 Conclusion

What have we learned about the nature of the processes that are involved in stopping a motor response? First, this thesis presented an alternative viewpoint for explaining longer stop latencies for primary-task responses that are associated with reactive inhibitory control. In previous studies using an Eriksen flanker task, this interaction between stop-signal inhibition and reactive inhibition was interpreted in terms of a competition for the same limited resources (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Ridderinkhof, Band, & Logan, 1999). The data presented in this thesis suggested an alternative explanation. On-line tracking of

response force exerted by the participant showed that the duration of stop-signal processes is longer for more forceful responses, compared to less forceful responses. Thus, contrary to common sense, stopping is less easy when one is inclined to hold back the go response. This situation was studied in Chapter 2 where subjects were warned of an imminent nogo signal, and in Chapter 3 where go signals occurred rarely in a trial sequence of frequent nogo signals.

Second, this thesis elaborated the work on the development of inhibitory control by Dempster (1993). His '*susceptibility-to-interference model*' attributes a key role to the executive functions exercised by the prefrontal cortex and emphasizes active hierarchical control of a lower force by a higher force as key-construct. This model integrates developmental research which suggests that resistance to interference contributes to diverse expressions of cognitive development and neuropsychological research, which indicates that the frontal lobes play a critical role in interference-sensitive tasks (Casey, Giedd, & Thomas, 2000; Van der Molen, 2000). Moreover, Dempster (1993) argued that inhibition should be conceptualized in terms of a family of processes. In his view, inhibition has a variety of operating characteristics that may vary on temporal (e.g., proactive, coactive, and retroactive), formal (motor, perceptual, and linguistic), and spatial (internal and external) dimensions. It was speculated that these varieties of inhibition have different developmental trajectories and so give rise to a stage-like quality in the development of a child's sensitivity to interference. The age-related improvement in simple stop control that are reported in this thesis agree with Dempster's conjecture that younger children are particularly sensitive to motor aspects of interference. In addition, our findings extend Dempster's notion of differential development trajectories by indicating a fractionation of simple and selective inhibitory control within the motor dimension.

Third, evidence that stopping is not the mere absence of a response was presented. Instead, stopping should be conceptualized as a response *per se*. Based on this assumption, we were able to show that (i) responses to stop signals, like those to go signals, are delayed when subjects have to discriminate between the execution of the inhibitory response or not (selective stopping; Chapter 4), that (ii) selective stopping is slower given less discriminable stop signals (Chapters 5 and 6), and (iii) that the stop process is influenced by irrelevant aspects of the stop signal (Chapter 6).

This thesis cannot be concluded without a few remarks on the horse-race model. The model has served us well by providing SSRT as an analytical tool. This thesis did not intend to explore, or to go beyond, the scope of the horse-race model. The present results illustrate the robustness of the horse-race model. The model provided a description of stop data obtained with visual stop signals, which is as the results usually reported with auditory stop signals (see also Van Boxtel, van der Molen, Jennings, & Brunia, 2001). In addition, the model proved to be valid if the stop-signal instruction was related to the response instruction (Van den Wildenberg & van der Molen, 2003a). Application of the model helped to relate response force to stop speed (Van den Wildenberg, van der Molen, & Logan, 2002) and indicated effects of neurostimulation on the speed of stopping and responding (Chapter 7). In conclusion, the data presented in this thesis generally proved to be interpretable in terms of the horse-race model (see Band, van der Molen, & Logan, 2003 for elaborate horse-race model simulations of the stop-signal procedure).

The quest for the nature of stop processes presently continues with current experiments that include Parkinson patients treated with deep brain stimulation. These studies include recordings of event-related brain potentials to elucidate the role of distinct neuroanatomical structures in cognitive and motor aspects of anticipatory behavior.

In closing, we are currently analyzing data provided by an electrophysiological investigation of inhibitory control of go responses in the Simon paradigm (Burle, Ridderinkhof, Ramautar, & van den Wildenberg, 2003). This stop-signal study included electromyographic as well as ERP recordings and on-line tracking of response force. The design of this study will enable us to compare two manifestations of within-trial cognitive control; one externally and one internally generated. First, the cognitive control triggered by the external auditory stop signal that is aimed at the inhibition of ongoing response activation, and second, the internal executive control associated with the detection and subsequent suppression of incorrect response activation (i.e., partial errors, see also Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002). Comparing physiological indices that are associated with partially inhibited stop-signal trials and non-signal trials with corrected partial errors may help to elucidate the cognitive processes involved in error monitoring, capable of preventing erroneous response activation from leading to an overt incorrect response.

... So we are not stopping, yet.

