

Response inhibition in conflict tasks is revealed in delta plots

K. Richard Ridderinkhof^{1,2}, Wery P. M. van den Wildenberg^{1,3}, Jasper Wijnen¹, & Boris Burle^{1,3}

¹ *Department of Psychology, Universiteit van Amsterdam, the Netherlands*

² *Department of Psychology, Leiden University, the Netherlands*

³ *Centre National de la Recherche Scientifique and Université de Provence, Laboratoire de Neurobiologie de la Cognition, Marseille, France*

Introduction

Dealing with conflicting response tendencies in human information processing is thought to be an important aspect of goal-directed behavior. In a choice reaction task, one type of stimulus may designate one particular response (e.g., a speeded button press with the left hand) whereas another type of stimulus designates an alternative response (e.g., a speeded button press with the right hand). The term *response inhibition* is used here descriptively to refer to the mechanism or set of processes that results in the containment of prepotent behavioral responses when such responses are reflex-like, premature, inappropriate, or incorrect; thus, response inhibition is a key instrument of executive attention. The exact neural mechanism (in terms of, e.g., the exact paths and projection sites of inhibitory neurons and interneurons) of this form of response inhibition is not entirely understood, but neuroimaging studies and patient work suggest that response inhibition is mediated by structures in (pre)frontal cortex and basal ganglia (e.g., Casey et al., 2002; Garavan et al., 2002; for a review see Band & van Boxtel, 1999). Functional neuroimaging studies have provided support for the alleged role of frontal brain areas in resolving response conflict (e.g., Bench et al., 1993; Bush et al., 1998; Carter et al., 1995b; Hazeltine et al., 2000; McKeown et al., 1998; Ullsperger & von Cramon, 2001). However, few studies have provided direct evidence for the role of response inhibition in resolving or preventing conflict.

Our main goal in this chapter is to present a method that allows us to examine the proficiency of response inhibition in behavioral (reaction time) data. We will review two

examples in which we use an analytical technique known as *delta-plot analysis* to highlight the role of response inhibition in resolving response conflict. The first study is on individual differences in resolving response conflict and included subjects in the normal population. In the second experiment, delta plots were used to mark inhibitory deficits in children diagnosed with Attention Deficit Hyperactivity Disorder (AD/HD). First, we will briefly introduce the conflict paradigm.

Response inhibition in conflict tasks

The choice reaction time (RT) tasks introduced by Stroop (1935), Simon (1990), and Eriksen (Eriksen & Eriksen, 1974) are prototypical representatives of experimental paradigms that induce conflicting responses. Responses are defined here as button presses with either the left or right hand. The signals employed in these tasks typically consist of two dimensions: a relevant one, on which the participant should base his/her response and an irrelevant one, unrelated to the task. In the Stroop task, the subject is asked to name the font color (task-relevant aspect) in which a color word (task-irrelevant aspect) is printed. Responses are slowed when the font color is different from the word itself (e.g. the word "red" printed in blue ink). In the arrow version of the Eriksen task, participants are instructed to issue a discriminative response based on the direction of a target arrow, and to ignore flanking arrows. Responses are typically slower when the flanking arrows point to the other direction as the central arrow, inducing conflict. In the Simon task, participants are instructed to generate a swift button-press response with either the right or the

left hand based on the color of a signal (relevant feature); for example, to press left to a green signal and to press right to a blue one. This signal can appear on the right or on the left side, and this task-irrelevant position-related aspect of the signal automatically activates the response associated with it. The typical observation in the Simon task is that RTs are slowed due to conflict occurring when the irrelevant feature of the stimulus activates the alternative response. When a signal is presented to the right, but its color designates a left-hand button press, we speak of *incongruent* trials. Signals that require a left-hand response and are also presented on the left side are referred to as *congruent trials*. RTs are typically slower to incongruent compared to congruent trials, a finding referred to as the *congruency effect* or *interference effect*.

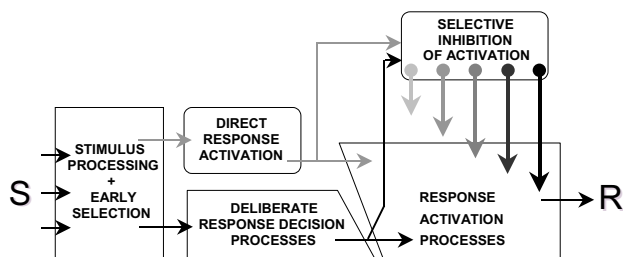


Figure 1 Elementary architecture of the dual-process model. The inhibition mechanism acts selectively upon response-activation processes that are associated with the direct response-activation route. Selective inhibition needs time to develop (represented by the length and color of the vertical arrows) before it can result in effective reduction of response activation processes.

To account for interference effects in conflict tasks, many authors have invoked a processing model that involves two distinct pathways (e.g., de Jong et al., 1994; Eimer et al., 1995; Kornblum et al., 1990; Ridderinkhof et al., 1995). A schematic representation of this type of model is depicted in Figure 1. Most significant, an attention-controlled pathway of stimulus-response translation is paralleled by a direct reflex-like route. The two routes converge at the level of response activation processes, that is, at the level where motor programs for specific behavioral responses are initiated and executed. An active response inhibition mechanism, serving to selectively reduce the activation of

specific responses, has often been suggested to keep inappropriate response activations in check (e.g., Eriksen & Schultz, 1979; Kopp et al., 1996). This selective response inhibition mechanism is the focus of the present chapter.

The Activation-Suppression Hypothesis: Predictions and Observations

In an explicit formulation, the *activation-suppression hypothesis* (Ridderinkhof, 2002a) holds that the behavioral response activated by the irrelevant stimulus features is selectively inhibited. This selective inhibition takes some time to build up, and hence becomes effective only after a given amount of time. A separate series of studies support these dynamics. Eimer (e.g., 1999; Eimer & Schlaghecken, 1998) presented masked prime stimuli that could be congruent or incongruent to subsequently presented target stimuli. Faster and more accurate performance was observed for congruent compared to incongruent trials, but only when the interval between prime and target was brief. At longer intervals, responses to congruent targets were slower and more error prone than responses to incongruent targets. Event-related brain potentials suggested that the masked primes initially generated direct activation of the corresponding response, which was subsequently inhibited. If the target was presented soon after the prime, the initial prime-based activation escaped inhibition and thus resulted in rapid responses to congruent trials but slow responses to incongruent trials. Conversely, if presentation of the target was delayed, then the initial prime-based response activation was selectively inhibited by the time response activation was elicited by the target. Thus, long delays are detrimental for responses to congruent trials, making them relatively slow and error-prone, as the *correct* response associated with the prime was being inhibited. Equally, responses to incongruent targets benefit from longer delays, such that they are relatively fast and accurate, as the incorrect response elicited by the prime was being inhibited. The activation-suppression hypothesis has several implications in the Simon task. Because

of the same dynamics described above (in particular the gradual build-up of response inhibition as time progresses across a trial), slower responses will be more affected by selective response inhibition than faster responses (see also Burle et al., 2002; Eimer, 1999). The automatic route will facilitate the correct response on congruent trials, but it will interfere with the correct response on incongruent trials. While this is true for fast responses, an additional factor comes into play for slower responses: with slower responses, the selective inhibition process has had time to develop, and thus the activation of the incorrect response along the direct route will be reduced. Correct responses to congruent trials will be less facilitated by the position-driven route, whereas correct responses to incongruent trials will be less delayed. Thus, congruency effects are affected by selective response inhibition more in slow than in fast responses.

Like most mental processes, selective response inhibition can be assumed to be subject to variability. The strength, onset time, and build-up rate of selective inhibition of the response activated by the direct route may vary inter-individually and with experimental manipulations. If selective inhibition results in a reduction of the congruency effect in slow responses, as argued above, then the more effective this selective inhibition, the more pronounced the influence on congruency effects in slow responses. These dynamics point to the need to examine RT distributions. Several tools are available for distributional analyses. Here we focus on *delta plots*. Delta plots are constructed by plotting the congruency effect as a function of response speed (de Jong et al., 1994; Ridderinkhof, 2002a). While delta plots prototypically have a positive slope (i.e., the effects of any experimental factor increases as a function of response speed), the notion that selective inhibition results in a reduction of the congruency effect in slow responses (outlined above) implies a different delta-plot pattern: the congruency effect should not increase linearly as a function of response speed, but instead level off

and become reduced for slow responses. If more effective selective inhibition results in a more pronounced reduction of congruency effects in slow responses, as argued above, then the leveling off of the delta plot should be more pronounced in individuals that are more proficient in response inhibition than in less proficient individuals. Likewise, the leveling off of the delta plot should be more pronounced in experimental conditions that require more stringent response inhibition compared to less demanding conditions.

Ridderinkhof (2002a) designed a series of experiments to verify this prediction. The point of divergence between two delta plots (representing two different levels of inhibitory strength) was the critical variable in comparisons between conditions. Each experiment comprised a regular Simon task (that required a two-choice response on the basis of stimulus color) intermixed with a second task in which stimulus position was either irrelevant (Experiment 1) or relevant (Experiment 2). In the majority of trials in Experiment 1, subjects had to perform the regular Simon task. In the remaining trials, subjects responded as a function of stimulus shape. The location-driven information was irrelevant in both tasks, and hence could always be inhibited. In the second experiment, that used the same stimuli, the second task required a response on the basis of the location of the stimuli. Thus, in a small subset of trials location-driven information was relevant and should not be inhibited. Therefore, it would be disadvantageous to always inhibit location-driven direct response activation here. The regular Simon task was identical in all respects across the two Experiments, but nevertheless revealed opposite results depending on the nature of the intermixed task. Delta plots leveled off early and turned negative when location-driven activation could always be inhibited, but not when location was relevant in half of the trials.

Inhibitory control in the Simon task, as expressed in negative-going delta plots, is increased after errors (Ridderinkhof, 2002b).

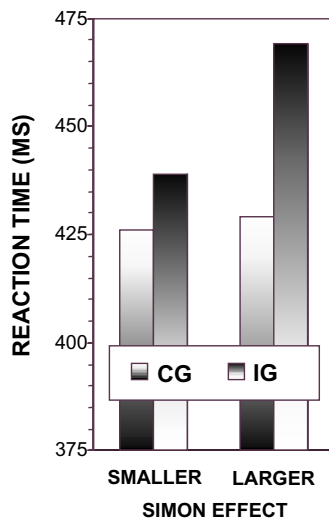


Figure 3 Delta plots for congruency effects in subjects with relatively small Simon effect and for subjects with relatively large Simon effect.

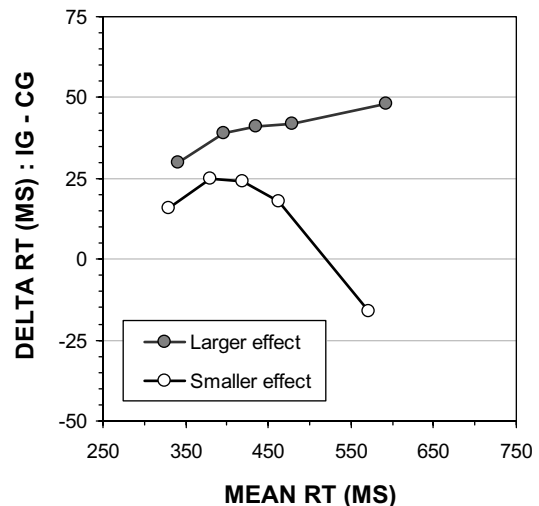


Figure 2 Mean RTs for congruent (CG) and incongruent (IG) conditions in subjects with relatively small Simon effects and in subjects with relatively large Simon effects.

Burle et al. (2002) used electromyographic recordings to extend this finding and demonstrate that this delta-plot effect in fact reflects an *on-line* act of inhibitory control. In a regular version of the Simon task, these authors showed that the leveling off and turning negative of the delta plot was most prominent on those trials that contained partial errors (i.e., sub-threshold activation of the muscles involved in the incorrect response prior to the threshold activation of the correct response). The operation of response inhibition is most critical on those trials on which the incorrect response is actually activated to the motor level, and this inhibitory engagement is expressed in the prominent deflection in the delta plot.

Illustrating the Utility of Delta Plot Analysis

Individual Differences. An example that illustrates the usefulness of delta plots in indexing response inhibition is taken from Ridderinkhof (2002a). One set of analyses used the delta plot techniques to demonstrate that, compared to subjects with larger Simon effects, subjects with smaller Simon effects displayed stronger inhibition effects, as expressed in the diverging slopes of the delta plots for RT. These patterns are shown in Figures 2 and 3.

Response Inhibition Deficits in AD/HD. Here we aim to point out the merits of delta plots to the study of individual differences, including developmental trends and clinical disorders, by applying them to investigate performance of children diagnosed with AD/HD. AD/HD is among the most prevalent childhood pathologies, and has been studied extensively in various branches of the cognitive neurosciences. Among the different theoretical perspectives in the study of AD/HD, several mainstream theories of neurocognitive deficits associated with AD/HD focus on the role of impulsivity and response inhibition (e.g., Barkley, 1997; Nigg, 2001). Studies that examined response conflict in the Eriksen flanker task have frequently reported AD/HD deficits (e.g., Carter et al., 1995a; Crone et al., 2003; Hooks et al., 1994; Jonkman et al., 1999).

Scheres et al. (2003) used the arrow version of the Eriksen flanker task to examine the performance of AD/HD children in comparison to matched controls. In this conflict task, participants are instructed to respond based on the direction of a target arrow, and to ignore flanking arrows. Responses are slower to incongruent stimulus displays, in which the flanking arrows point to the other direction as the central arrow. Ridderinkhof et al. (in press)

applied delta-plot analysis to the data from Scheres et al. (2003) to explore differences between AD/HD and control children (matched carefully in terms of age, gender, and IQ) with respect to the ability to inhibit task-irrelevant response activation. If AD/HD does involve a response-inhibition deficit, as hypothesized by current mainstream theories (e.g., Barkley, 1997; Nigg, 2001), then the slopes of (especially the slower segments of) delta plots for RT should level off more prominently for controls than for children with AD/HD. The congruency effect was larger for AD/HD children compared to controls (see Figure 4). Thus, overall performance measures suggest that compared to matched controls, children diagnosed as AD/HD are more sensitive to interference effects.

Closer examination of intra-individual performance variability revealed that the leveling off in the positive-going delta plots for RT was more pronounced and was manifest earlier in the distribution for controls than for AD/HD children (see Figure 5).

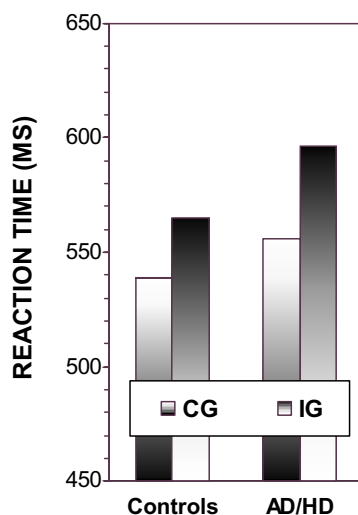


Figure 4 Mean RTs for congruent (CG) and incongruent (IG) conditions in AD/HD versus matched controls.

In accordance with the activation-suppression model, these findings can be interpreted to indicate that, compared to normal controls, AD/HD children show a deficiency in the selective inhibition of responses that were activated on the basis of flankers. These findings highlight the usefulness of the delta-plot technique in developmental and clinical research. These results provide thus far unique evidence for theories that emphasize response inhibition as a fundamental neurocognitive deficit in AD/HD (e.g., Barkley, 1997; Nigg, 2001). Note that these conclusions could not possibly have been obtained when analyses were confined to overall performance. The delta-plot technique has also been applied successfully to examine the pharmacological effects of alcohol (Ridderinkhof et al., 2002) and methylphenidate (Ridderinkhof et al., in press) on the efficiency of response inhibition in conflict tasks. Preliminary results of currently on-going research in our lab suggest that these distributional analyses are also useful in the study of eye movements (in particular the inhibition of reflexive saccades).

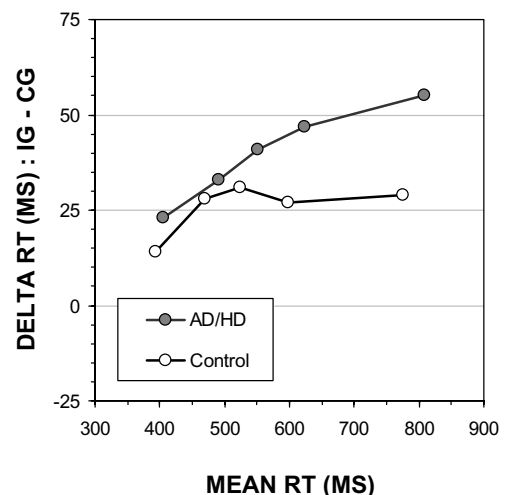


Figure 5 Delta plots for congruency effects in AD/HD versus matched controls.

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