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RESEARCH NOTE

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Fore-period effect and stop-signal reaction time

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Abstract The effect of response readiness on the stop-signal reaction time (SSRT) in a stop-signal task was examined, with the stop-signal delay updated following a staircase procedure. We computed SSRT on the basis of a horse race model. A fore-period effect was computed, which described subjects' readiness to respond to the GO signal. The results showed that the fore-period effect correlated positively with SSRT, providing evidence of the effect of response prepotency on stop signal processing. This finding suggests that response readiness needs to be accounted for in examining response inhibition in a stop-signal task.

Keywords Response inhibition · Impulsivity · Stop signal task · Go/no-go · Attention

Introduction

Inhibitory control provides an important regulatory function for the execution of context-appropriate behaviors. It is well known that patients with brain disorders can have difficulty with inhibitory control and manifest behavioral impulsivity. For instance, lesions in the ventral prefrontal cortex contribute to emotional changes and socially inappropriate behaviors (Rolls et al. 1994). A wide range of psychiatric conditions also implicates deficits in behavioral inhibition (Moeller et al. 2001). For instance, a high level of impulsivity is frequently a component of antisocial personality disorder. Impulsivity has also been implicated in substance use, attention deficit and conduct disorders. Involved in virtually every aspect of human behavior, inhibitory mechanisms are thus central to our understanding of both normal and abnormal brain functions.

In laboratory settings the stop-signal task has been a valuable tool to study response inhibition (Logan 1994). There are two types of trials in this behavioral task: in go trials, the predominant type of trials, one responds to a go signal generally as quickly as possible; in stop trials, an additional stop signal follows the go signal and one is to withhold the response upon seeing the stop signal. The ease with which one can withhold a response depends on the time interval between the go and stop signals, or the stop-signal delay (SSD): the longer the SSD, the more difficult it is for one to stop and vice versa.

Response inhibition in the stop-signal task can be characterized in several ways. First, by using a few different, well-spaced SSDs and computing the percentage of the stop trials with the response successfully withheld at each SSD (higher percentage at short SSDs), one can construct an inhibitory function for individual subjects. In other words, the inhibitory function represents an integrated percentage of successful stop trials. The inhibitory function can then be compared between different subject groups. Another index useful to characterize response inhibition is the stop-signal reaction time or SSRT, which describes the time for the stop signal to be processed so that a response can be withheld. Based on a horse race model, behavioral performance in the stop-signal task can be interpreted in terms of statistically independent go and stop processes racing toward their finishing line or activation threshold (Logan and Cowan 1984). The horse race model allows estimation of the SSRT based on the subject's probability of inhibiting responses to the stop signal and the distribution of RT in the go trials (Logan 1994). A longer SSRT indicates poor response inhibition. Finally, SSRT in the stop-signal task can also be obtained via a staircase procedure to update SSD trial by trial. The SSD decreases by a specified step (to make it easier for the subject to stop at the stop signal) if the subject fails at a previous stop trial and increases by the same step if the subject succeeds. By

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following the staircase procedure, one can achieve a success rate of approximately 50% in the stop trials. A "critical" SSD can be computed that represents the time delay required for the subject to succeed in withholding a response in the stop trials half of the time (Levitt 1970). The SSRT is then estimated by subtracting the "critical" SSD from the average RT of the go trials. The two behavioral indices, the inhibitory function and SSRT, have been widely used to describe response inhibition in people with neurological (Aaron et al. 2003; Dimitrov et al. 2003; Rieger et al. 2003; Stewart and Tannock 1999) or psychiatric conditions (Armstrong and Munoz 2003; Badcock et al. 2002; Dimoska et al. 2003; Fillmore and Rush 2002; Oosterlaan and Sergeant 1996; Overtoom et al. 2002; Rubia et al. 1998; Schachar et al. 1995). These patients were invariably found to be impaired, compared to healthy control subjects.

The stop-signal task is well suited to study inhibitory function since the behavioral outcome is relatively well defined. Moreover, the systems involved in sensorimotor transformation and decision-making can be experimentally manipulated. For instance, varying the contrast of a visual stop signal provides clues to whether a difference in response inhibition originates from an alteration in sensory processing. Having the subjects respond against different weight loads in go trials allows one to evaluate the possibility that altered inhibitory function results from a change in motor control. The latter can be imposed, for example, by having subjects resist the gravitational drop of a response key, which varies in weight in different go trials. Although sensory and motor functions seem peripheral to the decision stage, they are important to control in order to attribute impaired performance to a deficit in inhibitory function. This issue merits particular consideration when medications known to affect sensory/motor functions (e.g., antipsychotics) or when diseases that compromise sensory/motor functions (e.g., Parkinson's disease) are involved in the study.

Another, better known but perhaps more elusive, factor that one needs to control is response readiness. Response readiness is associated with one's general motivation and ability to sustain concentration on a task and frequently is compromised in patients with a neurological or psychiatric disorder. In studies comparing response inhibition between patients and healthy controls, one often adopts a method to ensure that the RT as an index of the general motivation of the patients does not differ from that of the control subjects. For instance, Gauggel et al.(2004) showed that SSRT prolonged in patients with Parkinson's disease despite comparable primary task RT between patients and controls (Gauggel et al. 2004). On the other hand, response readiness can also be selective to the go signal and thus determines the allocation of processing resources to the go signal. The question thus arises whether the emphasis on reaction time results in a biased readiness or attention to the go signal in the patients, leading to a slower processing of the stop-signal and a longer stop-signal reaction time.

It is well documented that RT decreases with an increased duration for response preparation in a reaction time task (Bertelson and Tisseyre 1968; Woodrow 1914). This fore-period effect describes the readiness level at which a subject is about to respond to the go signal. In the present study it is investigated whether there is a relationship between the fore-period effect and SSRT.

Methods

Subjects

Eighteen young adults participated in the study, all of whom consented after they were given a detailed description of the study, according to institute guidelines. All aspects of the study were in agreement with the ethical guidelines of the 1964 Declaration of Helsinki. All subjects had normal or corrected-to-normal vision and denied ever having neurological or psychiatric illnesses or using illicit substances.

Behavioral task and experimental procedures

A simple reaction time task was employed in this stop-signal paradigm. Fig.1A illustrates the stop-signal task. There were two trial types: "go" and "stop." A small dot appeared on the computer screen to engage attention and eye fixation at the beginning of a go trial. After a randomized time interval selected from a continuous uniform distribution between 1 and 2 s, the dot turned into a circle, which subtended approximately 2° of visual angle. The circle served as an imperative stimulus and the subjects were instructed to quickly press a mouse button at the "go" signal but not before. The circle vanished at button press or after 1 s had elapsed, whichever came first, and the trial terminated. Two-thirds of all trials were go trials. In a stop trial, an additional "X," the "stop" signal, appeared after the go signal. The subjects were told to withhold button press if they saw the stop signal. Clearly it would be easier for the subject to withhold the response if the stop signal appeared immediately or early after the go signal, and the reverse applied if the time interval between the stop- and the go signals (or the SSD) was extended. The SSD started at 200 ms and varied from one stop trial to the next according to a staircase procedure: if the subject succeeded in withholding the response, the SSD increased by 64 ms; conversely, if they failed, SSD decreased by 64 ms. The stop trials constituted the remaining one-third of all trials. There were 360 (240 go and 120 stop) trials in an experiment. The subjects were instructed to respond quickly to the go signal, while keeping in mind that there would be a stop signal in some trials. All subjects were given approximately 20 practice trials before the study and confirmed that they understood the

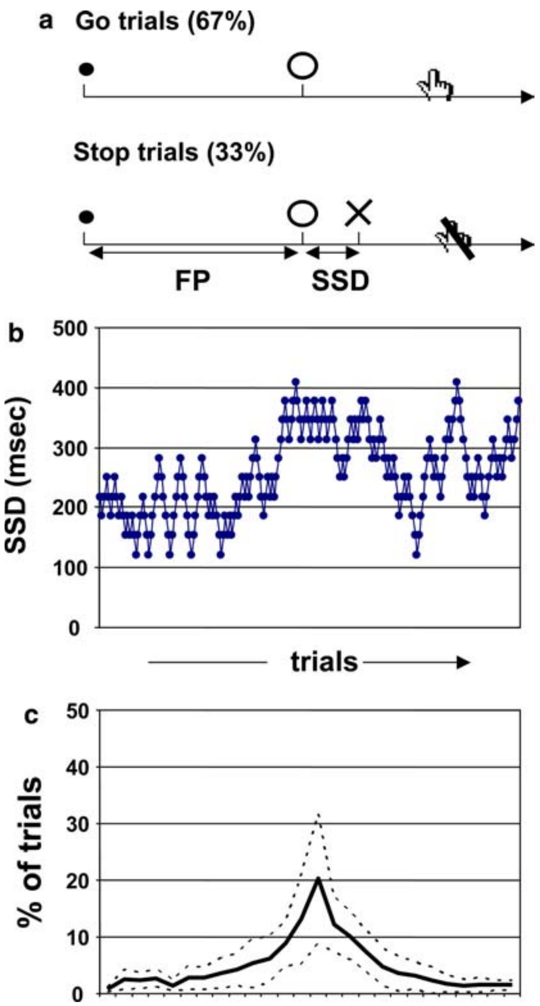

Fig. 1 The stop-signal paradigm. **a** Two-thirds of all trials were go trials, in which a circle (the "go" signal) replaced the fixation point after a randomized time interval anywhere between 1 and 2 s (fore-period or FP). Subjects were instructed to press a mouse button to the go signal. The remaining one-third of trials was stop trials, in which an additional "X" (the "stop" signal) appeared after the go signal, asking the subjects to withhold their button press. The time interval between the go and the stop signal, or the SSD, started with 200 ms and got updated trial by trial using a staircase procedure. **b** An example data set of SSD updated with a step of 32 ms obtained in a pilot experiment. The SSD fluctuated mostly between 100 and 400 ms. **c** RT distribution of go trials. The RTs of go trials were binned at 50 ms for each individual subject. The frequency distributions of all 18 subjects were then aligned at the peak frequency and averaged throughout all bins. Each panel shows the mean (*solid line*) ± SD(*dashed lines*) of the frequency

task. With the staircase procedure it was anticipated that the subjects would succeed in withholding the response in approximately 50% of the stop trials.

Results

General performance

The subjects successfully withheld their response in 50.5 ± 2.8 (mean ± SD) of the stop trials, with a reaction time of 547 ± 153 ms (mean ± SD) and following a close-to-normal distribution (skewness = 0.34, Fig 1c). For each individual subject a "critical" SSD was computed, which estimated the time difference between the go and the stop signals where the subject succeeded in approximately 50% of the trials in withholding a response (Levitt 1970). Then SSRT was computed by subtracting the critical SSD from the mean RT. SSRT ranged from 105 to 267 ms and averaged 181 ± 51 ms (mean ± SD).

Fore-period effect and SSPT

For each subject, the trials were divided into two groups, one with a fore-period of less than 1,500 ms (the approximate mean duration of the fore-period) and the other with one equal to or longer than 1,500 ms. Fore-period effect = mean RT for short fore-period (< 1,500 ms) - mean RT for long fore-period (≥1,500 ms). An *z* test was performed and the *z* value was used as an index of the fore-period effect for each individual subject. Linear regression showed that the fore-period effect was significantly correlated with SSRT (Pearson $r = 0.51$, $P < 0.03$, Fig. 2). On the other hand, there was no correlation between RT and SSRT ($P = 0.49$). Since the go trials' RT distribution was somewhat skewed, we also computed SSRT based on the median RT for individual subjects. Ranging from 99 to 258 ms and averaging 181 ± 46 ms (mean ± SD), the SSRT thus computed also correlated positively with the fore-period effect (Pearson $r = 0.55$, $P < 0.02$).

Discussion

It has been demonstrated in the current study that the fore-period effect, as an index of response readiness to

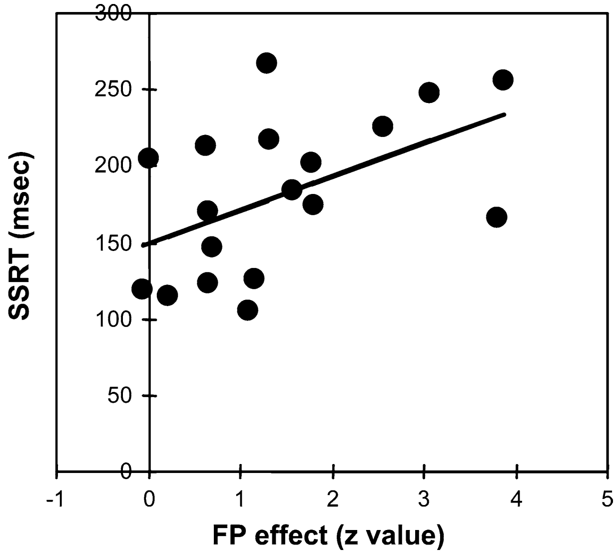

Fig. 2 SSRT correlates positively with the fore-period (FP) effect. Each data point represents an individual subject

the go signal, is correlated with the stop-signal reaction time in the stop-signal task. Response readiness to the go signal leads to preferential processing of the go signal, which, in situations where processing resources are limited, delays the processing of the stop signal.

As outlined above, the stop-signal task is widely used to study response inhibition in patients with neurological or psychiatric disorders. Compared to healthy control subjects, the patients are invariably found to be impaired, in terms of an increased SSRT or a diminished inhibitory function. To demonstrate that the impairment is more than deteriorated general performance in the stop-signal task, one often times verifies that the RT of the primary task (go trials) does not differ between patient and control groups. In cases where the primary task RT is prolonged in patients, one resorts to correlation and covariance analyses to show that the increase in SSRT is independent of go trials RT and that the increase in SSRT still holds after the difference in go trials RT is accounted for (e.g., Williams et al. 1999). While matching patient and control subjects in their primary task RT rules out general cognitive slowing or impaired vigilant attention as a factor that contributes to prolonged SSRT, the present results demonstrate that response readiness to the go signal should also be controlled for. Fig. 3 provides a conceptual framework to this end. Stop-signal reaction time or inhibitory function is evaluated against the fore-period effect as an index for response readiness to the go signal. A difference in response inhibition function between patients and controls can simply result from disparity in this selective response readiness. Statistics with the fore-period as a covariate would rule out this nuisance effect and document change in the response inhibition function independent of selective response readiness.

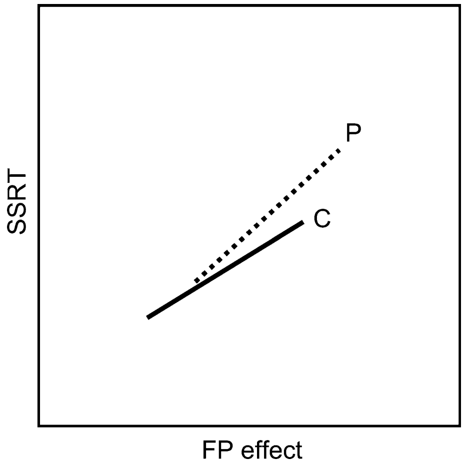

Fig. 3 A schematic illustrating the conceptual framework for examining inhibition function independent of attention in patient (*P*), compared to control (*C*) subjects. Both control and patient subjects demonstrate a similar linear association between SSRT and fore-period or FP effect. Increased SSRT in the patients could potentially result from a biased response readiness to the go signal (FP effect) in the stop-signal task

A recent study manipulated response readiness by cueing subjects of an imminent onset of a no-go signal during test episodes in a choice RT go/no-go study (Wildenberg et al. 2002). Counter-intuitively, they found that no-go signal processing was delayed, instead of being expedited, during episodes of decreased response readiness. The authors suggested that reduced response readiness might give rise to more forceful responses that were more difficult to inhibit. This is an interesting and tenable hypothesis, which can be verified by EMG recordings in future studies. Alternatively, one could postulate that in episodes preceded by a no-go signal cue, subjects might have adopted a conservative response strategy such that their general motivation level or vigilant attention imparted disadvantage not only upon go but also no-go signal processing, resulting in prolonged RT and SSRT. In our current study, response readiness varied from trial to trial, thus pre-empting any blocked effects of altered general arousal or vigilant attention. It was observed that fore-period, or response readiness, effect correlated positively with SSRT. It thus appeared that the response readiness that was built into our behavioral paradigm better reflected its selective association with the go signal than that of Wildenberg et al. 2002. More studies are warranted to examine the effect of the general and selective aspects of response readiness on stop signal processing. Indeed, one needs to investigate whether selective attention to the stop signal or "no-response" readiness can also affect stop signal processing.

Finally, several recent studies by Colonius et al. found that at short stop-signal delays the reaction times of certain stop failure trials were longer than predicted by the horse race model (Colonius et al. 2001; Özyurt et al. 2003). These results supported an inhibitory interaction between the go and stop processes—presentation of the stop signal impeded the processing of the go signal, or conversely, the processing of the go signal already in progress delayed processing of the stop signal (Özyurt et al.2003). The current finding of a positive correlation between fore-period effect and SSRT also suggests that go and stop signal processing may not be independent as assumed by the horse race model (Logan 1994). Further studies are required to verify the interactions and to study the temporal dynamics of these interactions.

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References

Armstrong IT, Munoz DP (2003) Inhibitory control of eye movements during oculomotor countermanding in adults with attention-deficit hyperactivity disorder. Exp Brain Res 152:444–452

Aaron AR, Fletcher PC, Bullmore ET, Sahakian BJ, Robbins TW (2003) Stop-signal inhibition disrupted by damage to right inferior frontal gyrus in humans. Nature Neurosci 6:115–116

Badcock JC, Michie PT, Johnson L, Combrinck J (2002) Acts of control in schizophrenia: dissociating the components of inhibition. Psychol Med 32:287–297

Bertelson P, Tisseyre F (1968) The time-course of preparation with regular and irregular foreperiods. Q J Exp Psychol 20:297–300

Colonius H, Özyurt J, Arndt PA (2001) Countermanding saccades with auditory stop signals: Testing the race model. Vision Res 41:1951–1968

Dimitrov M, Nakic M, Elpern-Waxman J, Granetz J, O'Grady J, Phipps M, Milne E, Logan GD, Hasher L, Grafman J (2003) Inhibitory attentional control in patients with frontal lobe damage. Brain Cognit 52:258–270

Dimoska A, Johnstone SJ, Barry RJ, Clarke AR (2003) Inhibitory motor control in children with attention-deficit/hyperactivity disorder: event-related potentials in the stop-signal paradigm. Biol Psychiatr 54:1345–1354

Fillmore MT, Rush CR (2002) Impaired inhibitory control of behavior in chronic cocaine users. Drug Alcohol Depend 66:265–273

Gauggel S, Rieger M, Feghoff TA (2004) Inhibition of ongoing responses in patients with Parkinson's disease. J Neurol Neurosurg Psychiatr 75:539–44

Levitt H (1970) Transformed up-down methods in psychoacoustics. J Acoust Soc Am 49:467–477

Logan GD (1994) On the ability to inhibit thought and action: a user's guide to stop signal paradigm.In: Dagenbach D, Carr TH (eds) Inhibitory processes in attention, memory and language. Academic, San Diego, pp 189–239

Logan GD, Cowan WB (1984) On the ability to inhibit thought and action: a theory of an act of control. Psychol Rev 91:295–327

Moeller FG, Barratt ES, Dougherty DM, Schmitz JM, Swann AC (2001) Psychiatric aspects of impulsivity. Am J Psychiatr 158:1783–1793

Oosterlaan J, Sergeant JA (1996) Inhibition in ADHD, aggressive, and anxious children: a biologically based model of child psychopathology. J Abnorm Child Psychol 24:19–36

Overtoom CC, Kenemans JL, Verbaten MN, Kemner C, van der Molen MW, van Engeland H, Buitelaar JK, Koelega HS (2002) Inhibition in children with attention-deficit/hyperactivity disorder: a psychophysiological study of the stop task. Biol Psychiatr 51:668–676

Özyurt J, Colonius H, Arndt PA (2003) Countermanding saccades: evidence against independent processing of go and stop signals. Percept Psychophys 65:420–428

Rieger M, Gauggel S, Burmeister K (2003) Inhibition of ongoing responses following frontal, nonfrontal, and basal ganglia lesions. Neuropsychol 17:272–282

Rolls ET, Hornak J, Wade D, McGrath J (1994) Emotion-related learning in patients with social and emotional changes associated with frontal lobe damage. J Neurol Neurosurg Psychiatr 57:1518–1524

Rubia K, Oosterlaan J, Sergeant JA, Brandeis D, von Leeuwen T (1998) Inhibitory dysfunction in hyperactive boys. Behav Brain Res 94:25–32

Schachar R, Mota VL, Logan GD, Tannoc R, Klim P. (1995) Deficient inhibitory control in attention deficit hyperactivity disorder. J Abnorm Child Psychol 23:411–437

Stewart JA, Tannock R (1999) Inhibitory control differences following mild head injury. Brain Cognit 41:411–416

van den Wildenberg WPM, van der Molen MW, Logan GD (2002) Reduced response readiness delays stop signal inhibition. Acta Psychol 111:155–169

Williams BR, Ponesse JS, Schachar RJ (1999) Development of inhibitory control across the life span. Development Psychol 35:205–213

Woodrow H (1914) The measurement of attention. Psychol Monogr 17:1–158