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Research report

Stop-signal task difficulty and the right inferior frontal gyrus

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HIGHLIGHTS

- The neural basis of task difficulty in the stop-signal task was examined.
- Participants were given equal time to inhibit cued responses.
- SSRT was inversely related to the probability of inhibition.
- The probability of inhibition was inversely related to right IFG activation.
- Time available for inhibition affects task difficulty and right IFG activation.

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ABSTRACT

The stop-signal paradigm is increasingly being used as a probe of response inhibition in basic and clinical neuroimaging research. The critical feature of this task is that a cued response is countermanded by a secondary 'stop-signal' stimulus offset from the first by a 'stop-signal delay'. Here we explored the role of task difficulty in the stop-signal task with the hypothesis that what is critical for successful inhibition is the time available for stopping, that we define as the difference between stop-signal onset and the expected response time (approximated by reaction time from previous trial). We also used functional magnetic resonance imaging (fMRI) to examine how the time available for stopping affects activity in the putative right inferior frontal gyrus and presupplementary motor area (right IFG-preSMA) network that is known to support stopping. While undergoing fMRI scanning, participants performed a stop-signal variant where the time available for stopping was kept approximately constant across participants, which enabled us to compare how the time available for stopping affected stop-signal task difficulty both within and between subjects. Importantly, all behavioural and neuroimaging data were consistent with previous findings. We found that the time available for stopping distinguished successful from unsuccessful inhibition trials, was independent of stop-signal delay, and affected successful inhibition depending upon individual SSRT. We also found that right IFG and adjacent anterior insula were more strongly activated during more difficult stopping. These findings may have critical implications for stop-signal studies that compare different patient or other groups using fixed stop-signal delays.

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1. Introduction

The ability to flexibly interrupt planned and on-going motor activation is termed response inhibition, which has a key role in goal-directed behaviour [1]. Response inhibition is often probed using the stop-signal paradigm [2] that requires participants to make reaction time responses to 'go' stimuli (the go task) and to attempt to inhibit responding when a second stimulus, the 'stop-signal', follows a go stimulus after a brief interval termed the stop-signal delay (the stop-signal task). A large body of evidence suggests that successful stop-signal task performance (stopping) is supported by a cortical network that includes the right inferior frontal gyrus (IFG) and presupplementary motor area (preSMA) that is activated during stopping regardless of the modality of the go response effector [3–5]. In recent years, researchers have begun using the stop-signal paradigm in the fMRI environment

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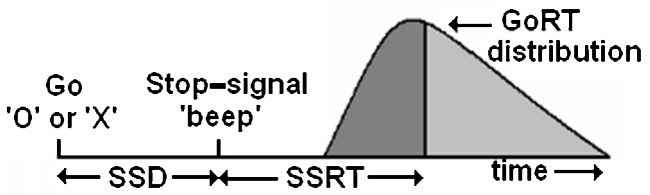

Fig. 1. The race model (adapted from [2]). The probability of responding at a given Stop-signal delay (SSD) is proportional to the portion of the distribution of correct Go task reaction times (GoRTs) that are too fast to be inhibited (P(r), dark grey portion on left), separating it from the portion of the distribution representing GoRTs that are slow enough to be inhibited (P(i), light grey portion on right). These portions are demarcated by a certain GoRT; the difference between this demarcation GoRT and SSD provides an estimate of the speed of response inhibition, the Stop-signal reaction time (SSRT).

to explore response inhibition impairments in a variety of patient groups including ADHD [6,7] and schizophrenia [8,9]. One largely unexplored area of stop-signal task performance concerns the determinants of task difficulty ('stop-signal task difficulty') and the impact of task difficulty on engagement of the right IFG-preSMA stopping network that may be important to consider when examining individual differences in stopping capabilities [10].

In the cognition literature, task difficulty has been construed in several ways, including variation (between conditions) of the effort [11] and duration [12] required for correct performance, resource allocation [13], and the probability of error [14]; or some combination thereof. Here we conceptualise task difficulty in the stop-signal task ('stop-signal task difficulty') as the probability of error determined by the relationship between the time available for inhibition and the speed of inhibition processes.

Stop-signal task difficulty in the past has been primarily manipulated by varying the delay between the onset of the go stimulus and the stop-signal stimulus, termed the *stop-signal delay* (SSD). That SSD affects stop-signal task difficulty is demonstrable by its effects upon the probability of successful inhibition (P(i)), the dependent measure of stop-signal task difficulty. The relationship between SSD and P(i) can be accounted for by a race model [2,15] that depicts stop-signal task performance as a race between independent go task processes and stop-signal task processes, where the winner determines whether inhibition is successful (*signal-inhibit trial*) or unsuccessful (*signal-respond trial*). The model suggests that if SSD is sufficiently short, all go task reaction times (GoRTs) will be inhibited (P(i) = 1), but as SSD increases P(i) decreases, until SSD is long enough for all GoRTs to escape inhibition (P(i) = 0). In their seminal publication, Logan and Cowan [2,15] showed that the race model could be used to estimate the speed of stop-signal task processes, which they termed the *stop-signal reaction time* (SSRT) (Fig. 1).

While SSD affects P(i), the capacity of SSD to predict stop-signal task difficulty is limited due to individual differences in GoRT and SSRT. Indeed the SSD that predicts a given P(i) in one individual may elicit a completely different P(i) in another. One particularly crucial factor is variation of GoRT that is partly under participants' control on a trial-to-trial strategic basis, increasing GoRT when they expect a stop-signal to occur and decreasing when not expected, with the aim of increasing P(i) [1,16]. The critical feature of this strategy is to increase the interval between stop-signal onset (SSD) and expected GoRT ($GoRT_E$), that is, to increase the *time available for stopping* (TAS[1]: $TAS = GoRT_E - SSD$). Hence for a given individual, longer TAS should make stopping easier (higher P(i)) compared to shorter TAS (lower P(i)). When assessing stop-signal task difficulty between-subjects however, the relationship between TAS and SSRT must also be considered. The race model suggests that if SSRT is shorter than TAS (SSRT < TAS), stopping processes are more likely to finish first resulting in a signal-inhibit trial, but if SSRT is longer than TAS (SSRT > TAS), then a signal-respond trial is more probable. This suggests that at a given TAS, participants with slower SSRT will exhibit lower P(i) than participants with faster SSRT; it follows that at a given TAS, participants with slower SSRT experience greater stop-signal task difficulty than participants with faster SSRT.

To explore the impact SSRT and TAS have upon stop-signal task difficulty, we used a variant where SSDs were set relative to an estimate of median GoRT as in many previous studies [2,18,19]. We chose this protocol as it keeps mean TAS (approximately) constant, hence stop-signal task difficulty should vary between-subjects as a function of SSRT. To examine stop-signal task difficulty within-subjects, we compared TAS and SSD[2] for signal-inhibit (TAS_I, SSD_I) compared to signal-respond trials (TAS_R, SSD_R). This requires knowledge of $GoRT_E$, however as no overt response is observed during stopping it is impossible to know $GoRT_E$ precisely. Fortunately, there is strong autocorrelation between successive GoRTs in stop-signal behavioural data [20], hence $GoRT_E$ may be estimated by the GoRT observed on the trial preceding a trial of interest. Additionally, we sought to determine independence of TAS_I from SSD_I by examining the correlation between these measures.

Finally, we sought to examine the impact stop-signal task difficulty has upon the right IFG-preSMA stopping network. In previous studies, researchers have used performance tracking algorithms to titrate an inhibition rate of 50% (i.e., P(i) = .5) so that the racing go task and stop-signal task processes are handicapped to elicit the same relative finishing times; when this is the case, the activation of right IFG [3,21–25] and preSMA [3,23,25,26] exhibit a negative relationship with SSRT between subjects. However, these studies do not directly address the impact of stop-signal task difficulty on activation in the right IFG-preSMA network between subjects as the adaptive SSD protocol decouples SSRT from stop-signal task difficulty, whereas with our paradigm SSRT and stop-signal task difficulty are related via their association with TAS.

To examine the impact of stop-signal task difficulty in the right IFG-preSMA stopping network (i) between-subjects we compared successful inhibition activation (signal-inhibit trials) in participants experiencing greater stop-signal task difficulty (lower P(i)) to participants experiencing less stop-signal task difficulty (higher P(i)), and (ii) within-subjects, we compared signal-inhibit trials of shorter TAS_I to those of longer TAS_I.

2. Methods

2.1. Participants

Fifteen healthy right-handed volunteers (aged 22–34, M = 27.5 years, SD = 3.7 years, 7 females) were tested. Self-report was used to screen for exclusion criteria that included a personal or family history of psychological or psychiatric disorders, a personal history of neurological disorders, brain injury or substance abuse in addition to standard MRI contraindications. The Human Research Ethics Committee of the University of Newcastle and the Hunter Area Health Research Ethics Committee approved this study. Written and informed consent was obtained from all participants according to the Helsinki declaration. Participants first attended an initial task practice session and later attended an fMRI scanning session.

2.2. Tasks and stimuli

Stimulus sequences began with a 5 s countdown, followed by a block of 220 trials lasting 5 min and 30 s. Two blocks were performed in practice sessions, and, six blocks were performed during fMRI scanning sessions. Go task stimuli were the letters O and X, presented with equal probability. Stop-signals (1000 Hz, 50 ms, 85 dB)

[1] This is identical to 'raw processing time' (rPT) in an alternate model of stopping processes recently proposed by Salinas and Stanford [17].

[2] Hereafter we use the notation SSD and TAS to indicate these values irrespective of performance, i.e., irrespective of whether trials are successful or unsuccessful stop-signal trials.

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