NeuroImage 139 (2016) 279–293

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

# Neural and behavioral correlates of selective stopping: Evidence for a different strategy adoption

Alberto J. Sánchez-Carmona [a,*], Jacobo Albert [a,b,*], José A. Hinojosa [a,c]

[a] Instituto Pluridisciplinar, Universidad Complutense de Madrid, Madrid, Spain
[b] Facultad de Psicología, Universidad Autónoma de Madrid, Madrid, Spain
[c] Facultad de Psicología, Universidad Complutense de Madrid, Madrid, Spain

ARTICLE INFO

*Article history:*
Received 11 December 2015
Accepted 23 June 2016
Available online 26 June 2016

*Keywords:*
Selective stopping
Stimulus-selective stop-signal task
Strategy
Event-related potentials (ERPs)
Source localization

ABSTRACT

The present study examined the neural and behavioral correlates of selective stopping, a form of inhibition that has scarcely been investigated. The selectivity of the inhibitory process is needed when individuals have to deal with an environment filled with multiple stimuli, some of which require inhibition and some of which do not. The stimulus-selective stop-signal task has been used to explore this issue assuming that all participants interrupt their ongoing responses selectively to stop but not to ignore signals. However, recent behavioral evidence suggests that some individuals do not carry out the task as experimenters expect, since they seemed to interrupt their response non-selectively to both signals. In the present study, we detected and controlled the cognitive strategy adopted by participants ($n = 57$) when they performed a stimulus-selective stop-signal task before comparing brain activation between conditions. In order to determine both the onset and the end of the response cancellation process underlying each strategy and to fully take advantage of the precise temporal resolution of event-related potentials, we used a mass univariate approach. Source localization techniques were also employed to estimate the neural underpinnings of the effects observed at the scalp level. Our results from scalp and source level analysis support the behavioral-based strategy classification. Specific effects were observed depending on the strategy adopted by participants. Thus, when contrasting successful stop versus ignore conditions, increased activation was only evident for subjects who were classified as using a strategy whereby the response interruption process was selective to stop trials. This increased activity was observed during the P3 time window in several left-lateralized brain regions, including middle and inferior frontal gyri, as well as parietal and insular cortices. By contrast, in those participants who used a strategy characterized by stopping non-selectively, no activation differences between successful stop and ignore conditions were observed at the estimated time at which response interruption process occurs. Overall, results from the current study highlight the importance of controlling for the different strategies adopted by participants to perform selective stopping tasks before analyzing brain activation patterns.



## Introduction

Response inhibition, defined as the ability to suppress unwanted thoughts and actions, plays a fundamental role acting as a basement for more complex cognitive capabilities (Verbruggen and Logan, 2008). Moreover, it allows people to flexibly adapt their behavior depending on current goals. The importance of this fundamental ability emerges clearly when considering its impairment in several neurological diseases and psychiatric disorders, such as Huntington's disease (Beste et al., 2008), obsessive-compulsive disorder (Bannon et al., 2002), attention-deficit/hyperactivity disorder (López-Martín et al., 2015) or substance abuse (Fillmore and Rush, 2002; Monterosso, 2005).

In order to investigate response inhibition, several experimental tasks have been designed. In particular, the so called go-no go and stop signal paradigms have widely been used to characterize the processes involved in response inhibition (Bari and Robbins, 2013; Chambers et al., 2009; Huster et al., 2013). In these tasks, a response tendency is first induced to participants (go condition), which has to be suddenly interrupted (no-go/stop condition). As a consequence the targeted response inhibition process is triggered. However, these two tasks differ in the specific nature of inhibition: the go/no-go task demands to withhold a prepotent but not yet initiated response, whereas the stop-signal task requires cancelling an already initiated response. Specifically, in the stop-signal task participants are usually asked to make button press responses to go stimuli and to interrupt their

* Corresponding authors at: Instituto Pluridisciplinar, Universidad Complutense de Madrid, Paseo Juan XXIII, n°1, 28040 Madrid, Spain.
*E-mail addresses:* albertosanchezcarmona@gmail.com (A.J. Sánchez-Carmona), jacobo.albert@uam.es (J. Albert).

http://dx.doi.org/10.1016/j.neuroimage.2016.06.043
1053-8119/

responses whenever a stop-signal is presented shortly after them. The main parameter of this task is the so called *stop signal delay* (SSD), which indexes the lag between the go stimulus and the stop-signal. Crucially, the probability of committing an inhibition error can be manipulated by modifying the duration of this delay, which allows for the calculation of the *stop signal reaction time* (SSRT). This has been considered to be a precise measure of the time that takes to inhibit a response. It is important to note that SSRT is an index of the several processes involved in the successful interruption of a motor response, which at least include the encoding of the stopping stimulus and the subsequent interruption of the ongoing response (Boucher et al., 2007). This estimation relies on the assumptions made by the horse-race model proposed by Logan and Cowan (1984) that describes the relative finishing time of the go (go RT) and stop (stop-respond RT) processes. Specifically, the go RT reflects the finishing time of the go process, whereas the stop-respond RT represents go RT on those trials with stop signals in which individuals fail to inhibit the response. In order to simplify the formal model of the estimation of SSRT, it is assumed that going and stopping processes (which are both active in stop trials) are independent (Logan and Cowan, 1984; Verbruggen and Logan, 2008; see also the interactive model proposed by Boucher et al., 2007). This means that the go RT distribution does not change once go responses have been initiated in stop signal trials. Importantly, this proposal assumes that a commission error will be made when going process finishes the race before stopping process. Thus, the horse-race model predicts that mean RTs on failed stop trials should be faster than mean RTs on go trials (Logan and Cowan, 1984; Verbruggen and Logan, 2009b). Finally, the model posits that the latency of the inhibition process can be measured based on the signal-response distribution by estimating the RT that represents the 50% likelihood of emitting a response and making a subsequent subtraction of the SSD from that value.

Several fMRI studies have tried to identify the neural basis of response inhibition. The results of these studies suggest that medial frontal regions (primarily, the pre-supplementary motor area; pre-SMA), the ventrolateral prefrontal cortex (inferior frontal gyrus) and the basal ganglia are particularly involved in inhibitory control (Chikazoe, 2010; Horn et al., 2003; Li et al., 2006; Li et al., 2008; Liddle et al., 2001). Of note, the chain of processes involved in the successful inhibition of a dominant response tendency is considered to last just a few hundred milliseconds (Huster et al., 2013). Therefore, the use of techniques with a high temporal resolution -such as event-related potentials or ERPs- may be suitable to complement fMRI data by providing insights on the temporal course of the processes associated with response inhibition. In this sense, prior ERPs studies with go/no-go and stop-signal tasks have already shown that two frontocentral components -the N2 (200–400 ms) and the P3 (300–600 ms)- are of particular interest when investigating response inhibition (Albert et al., 2013; Huster et al., 2013; Ramautar et al., 2004). Although the precise functional meaning of these components is still debatable, recent evidence suggests that the onset of the P3 may be a reliable index of response cancellation processes (Dimoska et al., 2006; Kok et al., 2004; Wessel and Aron, 2015). Moreover, P3 onset latency (defined as the temporal point at which differences between stop and go trials reached significance) has been found to match the time of the end of the stop process (as measured by the end of the SSRT) in the stop-signal paradigm (Wessel and Aron, 2015). In contrast, P3 peak latency is thought to reflect evaluative and reinforcement processes, which occur once the response has been successfully interrupted (Huster et al., 2013). With respect to the N2, it is however unclear whether this component reflects response interruption or other processing stages prior to response cancellation, such as perceptual mismatch, novelty processing or conflict detection (Folstein and Van Petten, 2008).

An important theoretical question concerns the processes underlying the experimental conditions typically used in studies with stop signal tasks. Notably, conclusions on the neural basis of stopping have been mainly drawn by comparing brain activity associated with successful stop trials and successful go trials, under the assumption that these conditions essentially differ in the activation of brain networks underlying response interruption. However, several studies have criticized this contrast for not being specific enough (Albert et al., 2013; Boehler et al., 2010; Dimoska et al., 2006; Etchell et al., 2012; Li et al., 2006; Sharp et al., 2010). In this sense, it should be noted that stop and go conditions not only differ in the involvement of response cancellation mechanisms per se but also in other processes (e.g., perceptual and cognitive). To try to solve this problem, in some studies successful stop trials were compared to unsuccessful stop trials. However, this solution has shown to be too restricted, since response interruption is involved to some extent in both conditions (Boehler et al., 2010). Moreover, compared with successful stopping, inhibition failures are associated with emotional processes (e.g., frustration) and error monitoring (Li et al., 2006). Finally, according to the assumptions made by the horse-race model, failed stop trials would result from a delay in the initiation of the stopping process compared to successful stop trials. This would make successful and failed stop trials difficult to compare.

In an attempt to isolate the brain activity specifically associated with the cancellation of an already initiated response, a new condition called *ignore* (or continue) has recently been introduced in the stop-signal paradigm. Although this new control condition still differs from the stop condition in decision-making processes (the ignore condition could be less relevant to the current task program than the stop one) and learning-related processes (the ignore condition leads to fewer errors than the stop one), it minimizes the aforementioned limitations by controlling both the novelty effect and sensory properties (Albert et al., 2013; Sharp et al., 2010, Etchell et al., 2012). Specifically, the sequence of events in the ignore condition resembles that of the stop condition since both trials start with a go stimulus which is followed by a signal stimulus after a delay. However, as opposed to the stop condition, participants in the ignore condition should continue responding after the signal stimulus as if it was a go trial. Moreover, the probabilities of occurrence of ignore and stop trials are kept equal, ruling out the possibility that activation differences between these two conditions reflect novelty/oddball processing. To date, only few fMRI (Boehler et al., 2010; Sharp et al., 2010), and ERP (Etchell et al., 2012) studies have followed this new approach.

In the behavioral domain, the results of studies that included ignore trials have led to the definition of the concept of *selective inhibition* (Bissett and Logan, 2014). It refers to the implementation of an inhibition that occurs only under specific circumstances related to certain stimulus features or to the response demanded by task instructions. Specifically, the inclusion of ignore trials in the so-called *stimulus-selective stopping* task would trigger slightly different processes (e.g., perceptual discrimination between stop and ignore signal) than those involved in the simple stop signal paradigm. Remarkably, it is assumed that in the stimulus-selective stopping paradigm participants selectively interrupt their responses to stop but not to ignore signals once the signal has been discriminated. However, as we will discuss later, recent evidence suggests that some participants perform the stimulus-selective stopping task by inhibiting selectively whereas others do not (because they stop their response whenever a signal occurs -ignore or stop-, and then restart the cancelled response if the signal presented was an ignore one Bissett and Logan, 2014). Interestingly, it is possible to identify the strategy adopted by each participant to perform a stimulus-selective stopping task (whether subjects inhibit selectively or not) by comparing RTs during no signal (go), ignore and stop trials (see decision matrix in Bissett & Logan, 2014, p. 457). Moreover, the independence between going and stopping assumed by the horse-race model can be tested separately for each strategy, which provides important information to establish the validity of the SSRT calculation.

Specifically, there is evidence of three distinct strategies that can be used to accomplish a stimulus-selective stop task (Bissett and Logan, 2014): *Stop then Discriminate* (*StD*), *independent Discriminate then Stop* (*iDtS*) *and dependent Discriminate then Stop* (*dDtS*). In the *StD* strategy,