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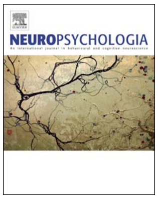

Sentential negation modulates inhibition in a stop-signal task. Evidence from behavioral and ERP data

David Beltrán[a,b,*], Mercedes Muñetón-Ayala[b,c], Manuel de Vega[a,b]

[a] *Department of Cognitive Psychology, Universidad de La Laguna, Tenerife, Spain*
[b] *Instituto Universitario de Neurociencia, Universidad de La Laguna, Tenerife, Spain*
[c] *Universidad de Antioquia, Colombia*

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ABSTRACT

Embodiment theories claim that language meaning involves sensory–motor simulation processes in the brain. A challenge for these theories, however, is to explain how abstract words, such as negations, are processed. In this article, we test the hypothesis that understanding sentential negation (e.g., You will not cut the bread) reuses the neural circuitry of response inhibition. Participants read manual action sentences with either affirmative or negative polarity, embedded in a Stop–Signal paradigm, while their EEG was recorded. The results showed that the inhibition-related N1 and P3 components were enhanced by successful inhibition. Most important, the early N1 amplitude was also modulated by sentence polarity, producing the largest values for successful inhibitions in the context of negative sentences, whereas no polarity effect was found for failing inhibition or go trials. The estimated neural sources for N1 effects revealed activations in the right inferior frontal gyrus, a typical inhibition-related area. Also, the estimated stop-signal reaction time was larger in trials with negative sentences. These results provide strong evidence that action-related negative sentences consume neural resources of response inhibition, resulting in less efficient processing in the Stop–Signal task.

1. Introduction

The embodied approach to language proposes that understanding action sentences induces resonance in the motor and premotor cortex to simulate the referred actions (e.g., Moody and Gennari, 2010; Aziz-Zadeh et al., 2006; de Vega et al., 2014). However, the meaning of negated action sentences is not easily explained in terms of embodied processes. For instance, the sentence “you do not cut the bread” refers to the absence of a manual action and, consequently, the motor simulation of the action seems unnecessary or irrelevant to understanding it. So, it is crucial for the embodied semantic approach to explore whether the theory can be extended to sentential negation. In this article, we tested a new hypothesis of negation, which posits that understanding negative statements could reuse the neural machinery of response inhibition.

Behavioral studies have shown that, in absence of previous context, negative sentences sometimes demand additional cognitive resources in comparison with affirmative sentences (Clark and Chase, 1972; Carpenter and Just, 1975), and that the presence of a negation reduces the accessibility of the negated concept (MacDonald and Just, 1989; Kaup, 2001; Kaup and Zwaan, 2003), although in occasions global discourse may contribute to suspend negated concept deactivation (Giora et al., 2007; Orenes et al., 2014). Also, studies with fMRI technique have demonstrated that negative action–related sentences generally reduce the activation of the motor and premotor cortex in comparison with their affirmative counterparts (Tettamanti et al., 2008; Tomasino et al., 2010). Moreover, TMS applied over the hand primary motor cortex reduced cortico-spinal excitability while participants read affirmative hand-action sentences, but not while they read negative hand-action sentences, indicating that activation of the motor cortex is somehow blocked by negation (Liuzza et al., 2011). Finally, behavioral measures obtained with action–sentence interference paradigms also showed reduced involvement of the motor cortex in negated hand-action sentences (Aravena et al., 2012; Bartoli et al., 2013).

The above studies clearly show the impact of negation on the cognitive (and neural) representations of sentence meaning, suggesting that negation reduces the strength of brain activations in specific cortices. However, the specific neural mechanism of negation itself is still unknown. In a previous study, we proposed that understanding sentential negation partially relies on the neurophysiological mechanisms of response inhibition (de Vega et al., 2016). This new hypothesis was supported by the following argument: negation seems to reduce or

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[*] Corresponding author at: Instituto Universitario de Neurociencia (IUNE), Universidad de La Laguna, 38205 Tenerife, Spain.
E-mail address: dbeltran@ull.edu.es (D. Beltrán).

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suppress the accessibility of previously activated representations. On the other hand, response inhibition consists of suppressing previously activated responses and also operates to suppress previously activated representations (Nakata et al., 2008; Smith et al., 2008). Therefore, we may expect that the general mechanisms of behavior inhibition or control is involved in the processing of negation.

Response inhibition consists of cancelling planned actions or suppressing alternative behaviors or representations that are inappropriate, unsafe, or no longer required (Chambers et al., 2009). Several cortical and subcortical structures play a significant role in inhibitory processes, such as the striate areas, the anterior cingulate cortex (ACC), the inferior parietal lobe (IPL), the insula, the temporo-parietal junction (TPJ), the supplementary motor area complex (pre-SMA and SMA proper), and the right inferior frontal gyrus (rIFG) (Nakata et al., 2008; Aron, 2011; Aron et al., 2014; Chambers et al., 2009; Swann et al., 2012; Juan and Muggleton, 2012). Two of these regions play an especially significant role: the SMA complex (which includes the pre-SMA and SMA proper) and the right IFG (as well as the left IFG to some extent). These regions show dense white matter connections, according to diffusion tensor imaging studies (Aron et al., 2007), and are also functionally interconnected, orchestrating the balance of motor excitation and inhibition during the performance of tasks which demand the suppression of a prepotent response, such as Go/NoGo, Stop–signal, flanker, task switching or Stroop tasks (Swann et al., 2012; Aron et al., 2007). Moreover, the pre-SMA and rIFG play a role not only in suppressing motor responses, but also in the cortical inhibition of competing cognitive representations (Nakata et al., 2008; Brier et al., 2010).

EEG studies with Go/NoGo and Stop–Signal paradigms, for their part, have provided a high-resolution temporal dynamics approach to cortical inhibition processes. They reported enhanced N1, N2, and/or P3 components of the ERP over fronto-central electrodes as signatures of response inhibition (Bokura et al., 2001; Smith et al., 2008; Maguire et al., 2009), and power enhancement in the theta band rhythms (4–7 Hz) over fronto-central sites and sometimes in the delta band (1–3 Hz) over centro-parietal sites for the NoGo (or Stop) trials (Nigbur et al., 2011; Huster et al., 2013; Cohen, 2014; Harper et al., 2014). A recent study performed in patients with intracranial EEG montage and cortico-cortical stimulation provided a temporal and spatial high-resolution approach to inhibition processes, showing directional neural flow from pre-SMA to rIFG while the participants performed a Stop–-Signal task (Swann et al., 2012).

Evidence that understanding sentential negation recruits cortical inhibition regions is still limited. In an fMRI study, activation was found in the rIFG during the comprehension of complex paragraphs involving negations (de Vega et al., 2014). Also, in an EEG study, it was reported that sentential negation, embedded in a Go/NoGo task, modulated the frontal theta rhythms, which are usually considered a signature of motor inhibition (de Vega et al., 2016). The authors found that the increase in theta rhythm power generally associated with NoGo trials was reduced by the presence of a negative compared to an affirmative sentence, demonstrating that processing the linguistic construal of negation may share neural processes with a concurrent response inhibition. Finally, a study with the TMS technique demonstrated that processing negated action sentences, compared to their affirmative counterparts, reduced cortico-spinal excitability, as measured by smaller MEP amplitude, whereas they showed larger silent period following stimulation on the motor cortex (Papeo et al., 2016). The duration of the silent period is an accepted marker of the activity in the GABAergic system (Schütz-Bosbach et al., 2008), and the authors conclude that negation recruits inhibitory processes.

In the current EEG study, we wanted to reinforce the idea that negation shares common neural networks with response inhibition, using ERP and source estimation analysis. To do this, participants received affirmative or negative polarity sentences embedded in a Stop–Signal task (SST). In the typical SST procedure, participants are always given a Go signal, but in some trials, after a variable delay, they also receive a Stop signal (e.g., a tone) indicating the necessity to withhold the already initiated response preparation. The Stop–Signal delay (SSD) contingently varies from trial to trial so as to produce around 50% successful stops; this is known as the staircase or tracking procedure. The Stop-Signal paradigm has been explained by the independent horse-race model, according to which in Stop trials, Go and Stop processes run independently and performance is characterized in terms of a race between the two (Logan and Cowan, 1984; Boucher et al., 2007); that is, whichever process finishes first determines whether the response is executed or successfully inhibited. The independence assumption implies that the distribution of Go processes on Stop trials (whether a response is made or not) is the same as the observed distribution of Go responses when there is no Stop signal. When the Stop–Signal delay (SSD) is short, the probability of successful inhibition is high; when the SSD is long, the probability of successful inhibition is low. The horse-race model makes it possible to estimate the Stop–Signal reaction time (SSRT), which is a cover parameter calculated from the empirical SSD with the 50% successful criterion and the reaction times to Go trials.

The Stop–signal task has several advantages over the Go/NoGo task. First, the sequence of Go and Stop signals ensures reactive inhibition (cued by the Stop signal) of a response that is underway (cued by the initial Go signal), whereas Go/NoGo tasks do not always produce enough response prepotency, and the NoGo trials could be more about deciding not to go than about countermanding an initiated response (Aron, 2011; Aron et al., 2014). Second, the Stop–Signal task makes it possible to estimate how long participants take to successfully generate the response inhibition, whereas in the Go/NoGo task, the inhibition-related NoGo trials do not produce any inhibition time measure (the only behavioral data correspond to commission errors or false alarms). Consequently, by combining the language task with the Stop–Signal task, we may expect to find a conspicuous interaction between sentence polarity and response inhibition, on both behavioral and ERP measures.

In the present dual-task procedure, each trial starts with the polarity marker (affirmative vs. negative) followed by the verb and then the Go cue followed in some cases by the Stop signal (see Fig. 1). Our main predictions concern successful Stop–Signal trials, which in the context of auditory Stop signals usually enhance the inhibition-related ERP components N1 and P3 (e.g. Bekker et al., 2005; Kenemans, 2015). We hypothesize that negative sentences, unlike affirmative sentences, consume inhibition resources, and differentially modulate the aforementioned components in Stop signal trials. A modulation of N1 would index the early demand of inhibition-related processes by negation, during the development of the ongoing Stop response. By contrast, a modulation of the P3 component would be likely related to the late reactive inhibition processes following the Stop response (e.g. Kenemans, 2015). Moreover, the source estimation of the ERP sentence polarity effects might find clusters of activation in the brain associated with inhibition-related regions, such as the rIFG and/or the pre-SMA. Finally, we hypothesize that the SSRT for negative sentence trials will be slower compared to the SSRT for affirmative sentence trials as a consequence of the limited inhibitory resources available in the former.

2. Method

2.1. Participants

A total of 28 undergraduate students of psychology participated in this experiment (23 females; mean age 20 years old, range 19–32). All participants gave informed consent and received course credit for their participation. All were neurologically healthy, right-handed native Spanish speakers and had normal or corrected-to-normal eyesight. Given the strict criterion applied in the tracking procedure, and the high demand of the dual-task paradigm used here, the data of 13 participants had to be removed from the analysis due to their failure to adapt to an average successful stopping of 55% (range 44.5–68%), leaving a final sample of 15 participants (13 females).