Universidad de La Laguna

Instituto Universitario de Neurociencia
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Facultad de Ciencias de la Salud. Sección de Psicología
Departamento de Psicología Cognitiva, Social y Organizacional
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Demonstrating the causal role of the motor and the inhibitory neural networks in the comprehension of action language

Tesis doctoral con mención internacional:
Francesca Vitale

Directores:
Dr. Manuel de Vega Rodríguez
Dr. Iván Padrón González

La Laguna, 2021

El Dr. Manuel de Vega Rodríguez y el Dr. Iván Padrón González, directores de la tesis de Vitale Francesca titulada "Demonstrating the causal role of the motor and the inhibitory neural networks in the comprehension of action language" aprueban la lectura de dicha tesis al considerar que cumple con las exigencias científicas y formales necesarias para su presentación.

La Laguna a 15 de abril de 2021

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INDEX

List of figures and tables:

Chapter 1:

Chapter 2:

(D) Temporal dynamics of deactivations for negative sentences compared to affirmative sentences, independently of the context, in the right middle frontal gyrus (left), in the right middle occipital gyrus (middle) and in the left pallidum (right).

Figure 2.2 (p. 64). (Papeo et al., 2016). A) Mean MEPs amplitude of action and state verbs for both affirmative and negative form, averaged by time B) and divided for the three-time interval.

Figure 2.3 (p. 66). (Chambers et al., 2009). Cortical substrate of the human brain regions involved in the mechanism of inhibitory response.

Figure 2.4 (p. 67). (Aron et al., 2011). The fronto-basal-ganglia model of inhibitory circuit for global stopping control.

Figure 2.5 (p. 69). (Beltrán et al., 2018). A) N1 component modulation (Successful Stop – Go and Unsuccessful Stop – Go) for affirmative (left) and negative (right) sentences. B) Brain source localization in the rIFG of the N1 component (left-top).

The mean current density values (bottom-left) indicated a statistical difference between affirmative and negative context in the successful trial, while no difference was shown for the unsuccessful trials. Temporal course of Negative-Affirmative contexts in the rIFG source for all the conditions (Go, Successful stop, Unsuccessful stop).

Figure 2.6 (p. 71). (Wilke et al., 2016). Representation of the CSP of a single trial after the MEP onset. The two cursor line (red) indicate the starting and the ending of the CSP.

Chapter 3:

Figure 3.1 (p. 85). Structure of experimental procedure. (A) Schematic representation of behavioral and neurophysiological sessions. (B) Example of a trial in the learning phase (translation: to open/a/notebook). (C) Example of a trial in the recall phase.

Chapter 4:

tests were conducted for every variable, ensuring no differences between the two type of verbs.

Abbreviations:

ACE: *Action-sentences Compatibility Effect*

BOLD: *Blood Oxygenation Level Dependent*

CS: *Conditioning stimulus*

CSE: *Corticospinal excitability*

CSP: *Cortical silent period*

EC: *Embodied cognition*

EEG: *Electroencephalography*

FDI: *First dorsal interosseous*

fMRI: *Functional Magnetic Resonance Imaging*

ICF: *intracortical facilitation*

ISIs: *interstimulus intervals*

M1: *Primary Motor cortex*

MEG: *Magnetoencephalography*

MEP: *Motor Evoked Potential*

pre-SMA: *pre-Supplementary Motor Area*

rIFG: *right Inferior Frontal Gyrus*

RIN: *Reusing Inhibition for Negation*

rMT: *resting Motor Threshold*

SICI: *short intracortical inhibition*

TBS: *Theta Burst Stimulation*

tDCS: *Transcranial Direct Current Stimulation*

    a-tDCS: *anodal Transcranial Direct Current Stimulation*

    c-tDCS: *cathodal Transcranial Direct Current Stimulation*

TMS: *Transcranial Magnetic Stimulation*

    rTMS: *repetitive Transcranial Magnetic Stimulation*

    sp-TMS: *single-pulse Transcranial Magnetic Stimulation* pp-TMS: *paired-pulse Transcranial Magnetic Stimulation*

TS: *Test stimulus*

Extended summary

In the last few decades, the notion that cognition is embodied, namely that it is grounded on the sensory and motor experiences has become an important approach in cognitive science. In the field of language, the embodied cognition (EC) approach posits that meaning understanding requires sensory and motor simulations of objects, events and situations described by words and sentences. With the term "simulation", we refer to a reactivation of perceptual, motor and introspective states that are acquired during experience with the world, the body and the mind. At the level of neural mechanisms, this means that language comprehension involves, to some extent, the activation of the same brain regions associated with the real world experiences that words and sentences refer to (Fischer & Zwaan, 2008; Gallese & Lakoff, 2005; García & Ibáñez, 2016; Jirak et al., 2010; Taylor & Zwaan, 2008).

The embodied cognition approach to language has received considerable empirical support (see below), particularly from studies showing that understanding action-related language is associated with increased activation of brain motor regions. However, this neural embodiment is considerably reduced when a negation marker is inserted into action sentences, leading to a disembodiment effect. In other words, the negation acts like a gate that reduces the accessibility of the negated concept, expressed at neural level by a decrease of motor activity. Most of the literature on embodiment and disembodiment (in negation) effects reports correlational results, that is, it offers evidence of an association between language comprehension and neural activity of the motor cortex. By contrast, using non-invasive brain stimulation methodologies, the experiments included in the present thesis provide evidence that such activity of the motor cortex is causally involved in the comprehension of action language.

Let us briefly summarize the state of the art of research on embodiment and disembodiment of language processes. To date, a large number of behavioral studies using a dual-task paradigm, reported that the processing of sentences referring to a directional action significantly influences the execution of a directionally compatible motor response (action-compatibility effect paradigm, ACE), suggesting that the motor areas activated in the action execution are also implicated in the comprehension of action-language (Borreggine & Kaschak, 2006; Boulenger et al., 2006; Buccino et al., 2005; Dalla Volta et al., 2009; de Vega et al., 2013; Glenberg & Kaschak, 2002; Kaschak & Borreggine, 2008; Sato et al., 2008; Taylor & Zwaan, 2008; Zwaan & Taylor, 2006). Further evidence was provided by several functional Magnetic Resonance Imaging (fMRI) experiments that revealed a somatotopic activation of the motor areas involved in the execution of the same movement expressed by action-related word (Olaf Hauk et al., 2004; Kemmerer et al., 2008; van Dam et al.,

2010) and sentences (Aziz-Zadeh et al., 2006; de Vega et al., 2014; Desai et al., 2010; Tettamanti et al., 2005), and that such activation is context dependent rather than automatic (Raposo et al., 2009). Another set of studies using electroencephalography (EEG), provide additional information, indicating that the motor cortices are recruited in action-language processing at an early temporal window after the word presentation (~ 200 ms) (Dalla Volta et al., 2014; Olaf Hauk & Pulvermüller, 2004; Pulvermüller et al., 2001), and that, this involvement is expressed by a suppression of mu and beta rhythms similar to the one observed during action observation or execution (Moreno et al., 2013, 2015; van Elk et al., 2010). Finally, neurophysiological studies suggest that, single-pulse transcranial magnetic stimulation (sp-TMS) applied to the primary motor cortex (M1) selectively influences the behavioural response for action words (Pulvermüller, Hauk, et al., 2005; Tomasino et al., 2008) and the comprehension of action-related language modulates motor cortical excitability (Buccino et al., 2005; Candidi et al., 2010; Innocenti et al., 2014; Papeo et al., 2009).

Overall, these evidences mainly point out that understanding language embedded in an action context engages the sensory and motor systems; however, they failed to assess the "necessity question". This question refers to the debate about whether motor activation is causally necessary in the processing of action-related meaning or is just an epiphenomenon, which occurs as a post-lexical simulation process with no relation to meaning (Leshinskaya & Caramazza, 2016; Mahon, 2015; Mahon & Caramazza, 2008; Papeo et al., 2013). One way to resolve the question is by means of causal techniques like repetitive Transcranial Magnetic Stimulation (rTMS) or transcranial direct current stimulation (tDCS), with the appropriate experimental designs. For instance, temporarily perturbing M1 activity by offline low-frequency rTMS delayed the processing of action words in a morphological task (Gerfo et al., 2008) and in a semantic task (Repetto et al., 2013), which indicates a functional relation between M1 activation and action language understanding. In the same line, online rTMS on M1 impaired the comprehension of action-related language in a priming semantic task (Kuipers et al., 2013) and in a concreteness judgment task (Vukovic et al., 2017). Compatibly, inhibitory tDCS on M1 reduced the learning of a novel action word (Liuzzi et al., 2010). However, some "paradoxical" effects have been reported; that is, the comprehension of action language improved, rather than getting worse, after the perturbation of the premotor cortex via rTMS (Willems et al., 2011) or tDCS (Gijssels et al., 2018; Niccolai et al., 2017).

The above results considerably support the idea that the motor system plays a causal role in the processing of action-related meaning. However, it should be noted that the experiments conducted so far not always give consistent results in the direction of the stimulation effects (facilitatory vs. inhibitory). In addition, they neglected some important issues. First, they focused mainly on evaluating the effect of inhibitory protocols ("virtual lesions"), paying less attention to the impact of the enhancement of motor activation on action language processing, which could be done using facilitatory stimulation protocols. Second, they usually collected online behavioral measures (i.e., reaction times to semantic judgments), while they did not test the involvement of the motor system in long-term cognitive processes such as memory. Third, when they measure behavioral effects of non-invasive stimulation, they do not monitor at the same time the physiological changes induced by the stimulation.

These crucial issues are addressed in detail in the current dissertation. Specifically, one objective is to provide further evidence for the functional role of M1 in the action-related language processing, by assessing for the first time its impact on memory performance for action language. To this aim, the first experiment induced the enhancement of motor activity, through a facilitatory tDCS protocol, to test whether it improves the performance in a language memory task consisting of memorizing action-related and attentional sentences. The participants performed two separated sessions; in one they received offline active tDCS (anodal/facilitatory or cathodal/inhibitory) on M1 and in the other they received sham tDCS, before undertaking the memory task. Additionally, since the stimulation, especially cathodal tDCS, is highly variable between subjects (Batsikadze et al., 2013; Jamil et al., 2017; Wiethoff et al., 2014), it was useful to assess the physiological effects of the tDCS on motor excitability, by measuring the motor-evoked potentials induced by sp-TMS. The results showed that applying off-line anodal tDCS, compared to the sham stimulation, led to a better memory for manual-action sentences but no for attentional sentences. No significant effect was observed for cathodal stimulation. Remarkably, the improvements in memory performance were predicted by the physiological changes induced by tDCS. In fact, the increase on motor excitability positively correlates with a better performance in the memory task, selectively for the action-language.

Assuming that, as mentioned before, the comprehension of action-related language requires the sensory motor simulation of the referred actions, sentential negation poses an interesting challenge for this embodiment view. How action sentences with a negation marker are represented or simulated? As neuroimaging studies have shown, negation applied to an action context, reduced the activation in motor and premotor cortices, compared to affirmative action sentences (Tettamanti et al., 2008; Tomasino et al., 2010). Consistently with these results, studies using dual task paradigms (Aravena et al., 2012; Bartoli et al., 2013), typing word paradigms (García-Marco et al., 2019) and passive reading (Foroni & Semin, 2013) revealed that negative action sentences reduced the activation of peripheral muscles, relative to their affirmative counterparts. In addition, processing negative action sentences selectively modulates motor cortex excitability compared to affirmative action sentences, while no similar effect of polarity was detected for abstract sentences (Liuzza et al., 2011; Papeo et al., 2016).

Altogether, the evidence suggests that the negation inserted in an action context reduces or blocks the access to the motor simulation of the negated concept, inducing a “disembodiment” effect. However, the neural mechanisms that produce this negation effect are still poorly understood. A recent proposal in this regard is the Reusing Inhibition for Negation (RIN) hypothesis, which, as its name suggests, asserts that the processing of negation reuses the mechanism of inhibitory control (Beltrán et al., 2018; de Vega et al., 2016; Liu et al., 2020). Some EEG studies, with dual-task paradigms, indirectly support the RIN hypothesis, showing that the processing of negative action sentences, compared to the affirmative ones, reduced the power of fronto-central theta rhythms (de Vega et al., 2016) and enhanced the amplitude of the ERP N1 component (Beltrán et al., 2018), in an immediately following inhibition-demanding task (NoGo or Stop trials). These facts are important because both theta rhythms and the N1component are indices of inhibitory activity. On the other hand, pre-setting an inhibitory state (NoGo trials) selectively affects the processing of negative action sentences (Liu et al., 2020). Notably, these EEG effects have an estimate source in the right inferior frontal gyrus (rIFG), which plays a crucial role in the response inhibition system (see Aron et al., 2014; Chambers et al., 2009 for reviewes). Further evidence supporting the RIN hypothesis showed that negative action language slowed the typing of manual action verbs (García-Marco et al., 2019), reflecting an inhibitory effect on motor programs, and increased the cortical silent period (Papeo et al., 2016), an index of the GABAergic inhibitory interneurons activity.

Although there are robust empirical results indicating a relationship between the inhibitory system and the “disembodied” effect of negation, they only allow to establish correlational conclusions. Indeed, to ensure the functional influence of the response inhibition mechanism in negation processing, a causal methodology is necessary. In order to fulfil this gap, in the second experiment of this dissertation we used an innovative stimulation technique that combined the registration of motor evoked potentials (MEPs) via sp-TMS on M1 and off-line rTMS on the inhibitory system. This protocol allows to test the causal influence of a target area transiently perturbed on M1 excitability. Specifically, to assess whether the inhibitory mechanism is functionally involved during the process of negation, we perturbed the rIFG activity, a key region of the inhibitory network, and then we measure the left M1 excitability during the presentation of action and attentional sentences, both constructed in affirmative or negative polarity format. In a control group, instead of active stimulation, sham rTMS was delivered over the vertex. Moreover, to evaluate whether the negation effect was exclusively associated with the verb presentation or it extended to later stages of sentences processing, we recorded the MEPs at two loci: the verb and the object. The results showed that in the sham group (baseline), the amplitude of MEP, recorded at the verb, was significantly lower for negative action-related sentences than for their affirmative counterparts and, more importantly, the rTMS over rIFG suppressed this inhibitory effect, leading to a comparable motor excitability for both conditions. No similar negation effect was observed on MEP either for the verb of attentional sentences nor for the object locus of any sentence. This pattern of results indicates the critical role of rIFG as regulator of M1 activation during the processing of negated action sentences.

In sum, this dissertation deals with the causal role of neural processes in embodied meaning:

1. The first experiment demonstrated, for the first time that the motor system activity is functionally involved in the memory for action language.
2. The second study provides novel evidence of a functional role of the neural mechanism of response inhibition in the "disembodied" effect of negative action language.

PART 1:

THEORY

Chapter 1:

The embodied cognition approach to language.

Language is one of the most defining characteristics of the human species, consisting of a highly complex symbolic capability with some important functions. It works as an inner voice to mentally speak to oneself as a tool for thinking, planning, remembering or just mind wandering. But, most obviously, language is a communication tool, with multiple pragmatic functions, such as the exchange of information with other humans about episodic events, concepts or mental states. Scholars of cognitive and social (neuro)science have devoted a great deal of effort to understand the mechanisms underlying this exciting and complex system of language. Cognitive psychology distinguishes between lower cognitive processes, which occur in an automated manner with lower level of consciousness, and higher cognitive processes that appear to exercise mental activities voluntarily with controlled awareness. Language, like thinking, memory or problem solving, is a higher cognitive process, while perception and action are typically lower cognitive processes.

The EC view, a relatively new approach, posits that there is no net separation between low and high cognitive processes; on the contrary, the individual sensorimotor experiences are closely linked to the higher cognitive functions. In fact, although in the last three decades different versions of EC theories have been developed, they all share the central notion that cognition is “grounded” in perception and action (Barsalou, 1999, 2008; Glenberg, 1997; Glenberg et al., 2013). The EC approaches contrast with other classical approaches to meaning, which assume that cognition, perception and action are temporally and functionally separated processes. Moreover, traditional theories of meaning are symbolist; namely, they claim that cognitive processes involve computations on abstract and amodal conceptual symbols, which are mental representations of different categories in the world and fundamental for most cognitive functions (Fodor, 1975, 1983; Fodor & Pylyshyn, 2015; Mahon & Caramazza, 2008; Pylyshyn, 1984). These mental representations are defined as amodal since they are independent from the sensorial modality of the input and, consequently, they are “encapsulated” in a modular semantic system, which is functionally separated from the systems of perception and action. For example, according to these theories, our concept of “cake” is an abstract and symbolic representation detached from any sensorimotor information related to the experience with any particular “cake”. When applied to linguistic comprehension, symbolistic theories claim that listening or reading words and sentences activates amodal representations in the mind, which constitute their meaning. Using the same example above, reading or listening to the word “cake”, would activate an abstract representation in the mind – the concept <cake> -, connected to other equally abstract representation such as <dessert>, <food>, <sweet>, none of which have relations with the visual, tactile, olfactory, gustatory or motor experience with the cakes. This perspective arise the issue that Harnad (1990) first defined as “*the symbol grounding problem”,* namely, arbitrary and abstract language symbols (such as words) cannot be understood only through their connection to others abstract and arbitrary symbols, otherwise language meaning remains in a sort of vicious circle (Harnad, 1990; Searle, 1980). That is, to understand the meaning of the linguistic forms (words and sentences) they need to be grounded in our bodies' perceptual and action systems (Barsalou, 1999; Glenberg, 1997). At the neural level, EC approach to language claims that the same structures activated during sensory, motor and emotional experiences are also involved in understanding linguistic material related to those experiences (Fischer & Zwaan, 2008; Gallese & Lakoff, 2005; García & Ibáñez, 2016; Glenberg et al., 2008; Jirak et al., 2010). For instance, referring to the example above, embodiment theories claim that reading or listening to the word "cake" recruits the same neural regions as those activated when individuals perceive (visual, auditory and somatosensory), behave or feel in front of a cake. In other words, processing words and sentences activate a "simulation" of the sensorimotor experiences the words and sentences refer to (e.g., how the cake look like, how does it taste, and so on).

Even though EC has achieved significant empirical demonstrations, it is still object of debate about whether the sensorimotor simulation plays a crucial role in language processing (for reviews see Fischer & Zwaan 2008; Gallese 2008; Glenberg et al. 2013), or the activation of sensorimotor areas is just epiphenomenal, resulting from "cascade" spreading activation between the conceptual system to the sensory and motor systems, which occurs after lexico-semantic (symbolic) processes (Chatterjee, 2010; Mahon, 2015; Mahon & Caramazza, 2008).

Demonstrating the functionality or causality of embodied processes in linguistic meaning is a crucial issue, and this thesis aims to provide direct evidence that the human motor cortex plays a functional role in the comprehension and memory of action related language. The first section of this chapter presents an exhaustive revision of the bibliography supporting the EC idea that understanding the meaning of an action words or sentences activates the motor circuits required to produce the action being described. The second section discusses those studies aiming at demonstrating, by means of the non-invasive brain stimulation techniques, that the activation of motor brain areas during the processing of action language is necessary to access at the linguistic meaning.

1.1 Action language understanding and the motor system: the mechanism of action simulation

What happens in your brain when you read or listen to an action-related sentence like "you grab the jackhammer to hang a picture"? The embodiment theory postulates that the neural structures active during the execution of the action "to grab a jackhammer", also play a role in understanding the semantic content of the same action verbally described (Gallese, 2007; Pulvermüller, 2005;

Rizzolatti & Craighero, 2007; Zwaan & Taylor, 2006). The rationale of this assumption relies on the phenomenon of action simulation discovered in the domain of action observation, namely, observing another person's actions involves recruitment of the same brain region activated when oneself performs the actions (Buccino et al., 2004; Fadiga et al., 1995; Grafton et al., 1996; Rizzolatti et al., 1996). Further investigations led to apply the concept of action simulation to the topic of action comprehension. The theorists assumed that to understand another's actions, we need to perform a mental simulation of the observed actions, by means of the so-called mirror neurons (Blakemore & Frith, 2005; Gallese et al., 1996; Jackson & Decety, 2004; Jeannerod, 2001; Rizzolatti & Arbib, 1998; Rizzolatti & Craighero, 2004; Wilson & Knoblich, 2005; Wolpert et al., 2003), since the observer recovers the intention that generated the observed action via his or her own internal action simulation. Finally, the concept of mental simulations has been extended to the language comprehension domain (Gallese & Lakoff, 2005; Rizzolatti & Arbib, 1998), leading the EC theorists of language understanding to assume that people understand action-related language through the mental simulation of the action the word or the sentences referred to (Barsalou, 2008; de Vega, 2015; Fischer & Zwaan, 2008; Glenberg & Kaschak, 2002).

Taking all this into account, action simulation theory on linguistic meaning has been developed, specifically investigating whether the processing of action language involves motor system activations. A conspicuous number of empirical results come from experimental methods using behavioural, neuroimaging e neurophysiological measures. The next subsections will describe the main studies associated with the different types of measured used; that is, behavioral evidence consisting of the interaction between action language and motor processes; neuroimaging evidence that action language activates the motoric regions of the brain, and electrophysiological studies, showing EEG and magnetoencephalography (MEG) signatures of motor processes associated with action language.

1.1.1 <u>The link between action and language</u>

Most of behavioral study have tested the EC theory on linguistic meaning by using dual-task paradigms. In a typical dual-task experiment, participants are asked to read or listen to sentences referring to actions while they have to perform a motor task designed to match or mismatch some feature of the action described in the sentences. The rationale is that, if action and language understanding shared the same motor processes, then, the comprehension of action sentences that match, for instance the direction, of the motor action will interact with the execution of the motor response. Glenberg and Kaschak (2002) first reported a facilitatory ACE, asking participants to make a sensibility judgment of sentences describes an action toward the body (e.g., “Meghan gave you a pen”), an action away from the body (“You gave Meghan a pen”), or nonsense sentences (“You write a clock”). To judge the sensibility, some participants were asked to respond “yes” moving the hand toward their body and respond “no” moving it away from their body to press the corresponding button, while for other participants the assignment of yes and no responses was the other way around. Participants were faster to evaluate the sentences sensibility when the direction of the action described in the sentences matched the direction of the movement required for responding “yes”. The ACE facilitation was confirmed by subsequent studies (Borreggine & Kaschak, 2006; Kaschak & Borreggine, 2008; Taylor & Zwaan, 2008; Zwaan & Taylor, 2006). Zwaan and Taylor (2006), for instance, conducted a series of experiments to provide more evidence of motor activation during online sentences comprehension, and to better understand the temporal dynamics at which the motor activation occurs. In their second experiment, participants were orally presented action sentences involving clockwise (e.g., “Jane started the car”) or counter-clockwise (e.g., “Julia set the clock back”) manual rotation, and were asked to make a speeded sensibility judgement by turning a knob. For half subjects turning the knob to the right (a clockwise response) corresponded to a sensible sentence and turning the knob to the left (a counter-clockwise response) corresponded to a non-sensible sentence, while the reverse was true for the other half. The results revealed faster sensibility judgment when the direction of the manual action described in the sentence matched the direction of the manual response, compared to the mismatching condition. Once confirmed the recruitment of motor processes in language understanding, the authors explored the onset of motor activation and the duration of the effect. Then to test these hypotheses, in the fourth experiment, sentences were presented word by word, and the participants had to turn a knob, either clockwise or counter-clockwise, to pass from the current word to the new one. Each sentence described a context that included either a clockwise (e.g., “To save / water / after / watering / the / garden / he / turned off / the / faucet.”) or a counter-clockwise (e.g., “He / realized / that the / music / was / too loud / so he / turned down / the / volume.”) manual-rotation movement. As in the previous experiment, the direction of the knob turning response could match or mismatch the orientation of the action described in the sentence. The results showed that, in match condition, participants turned the knob faster while they were reading the action verb, and besides, this facilitatory-match effect disappeared in the post verb word and in the final word of the sentences. No effect was detected in the mismatch condition. The authors assume that the facilitation was specific on the verb, since the following words shifted the attention away from the action. This assumption was further validated by the same authors (Taylor & Zwaan, 2008) using the same experimental paradigm, with a little change in the material. In this experiment, the verb was followed by an adverb to ensure that the focus on the action continued.

Indeed, the results confirmed the facilitatory ACE on the verb and extended the effect t the adverb, supporting the idea that motor simulation occurs as long as the focus is maintained on the action content. In the same way Kaschak and Borreggine (2008) explored the temporal dynamics of ACE (see also Borreggine and Kaschak 2006). Using the same material of Glenberg and Kaschak (2002), they asked participants to listen to sentences and to judge their sensibility at different time point after the stimulus onset, through a motor response towards or away from the body. Compared to previous experiment (Glenberg & Kaschak, 2002), the participants were unaware of the type of movement (towards or away from the body) they had to perform until a cue appeared, minimizing the possibility of programming the motor response as soon as the participants realized that the sentence was sensible, that is before the end of the sentences. The cue was presented at intervals of 500 ms, 1500 ms and 2000 ms after the onset of the sentences. The results evidenced an “early” ACE at an interval of 500 ms, which disappeared at later intervals like 1500 and 2000 ms, suggesting that the motor simulation of the action described in the sentence occur before the processing of the entire sentence. However, the sentences length was variable, then, a given interval in one sentence could correspond at a different processing moment for another sentence, and averaging the time respond recorded from a fixed time-point was a rather inaccurate measurement, since it could produce noisy data. Due to this reason, the authors calculated an ACE value, and reanalysed the data across items, showing that the motor simulation seemed to be centred between 500 and 1900 ms before the end of the sentence.

Taking together, these results support the idea that language understanding is grounded in bodily action.

All the experiments reported above, show a facilitatory ACE when the direction of the action depicted in the sentences and the direction of the response matched. However, other studies, using a different (Boulenger et al., 2006; Buccino et al., 2005; Dalla Volta et al., 2009; Sato et al., 2008) or similar (de Vega et al., 2013) dual task paradigm, reported interference rather than facilitation when motor and semantic properties matched. For instance, in the second behavioral study of Buccino et al. (2005), after carefully listening to hand-action-related sentences, foot-action sentences, and abstract sentences, participants had to give a motor response in the case of concrete sentences (hand-action-related sentences and foot-action-related sentences), while they had to restrain themselves from responding when the content sentence was abstract. Subjects were assigned to two groups that differed in the effector utilized to respond: in the first group, they used the right hand, while in the second group they used the right foot. Performing the motor-response with the hand, elicited slower reaction-time when the listened sentences expressed hand-related action, compared to foot-related action sentences. In contrast, participants were slower when they had to respond to foot-related action sentences using their foot, as compared to hand-action-related sentences. In other words, participants were slower when the effector needed to respond was the same involved in the action described in the sentence. These data strongly suggest that processing action language and motor responses involving the same motor representation compete for the same motor resources, interfering each other. These findings were further corroborate by Sato et al. (2008), using a similar Go-NoGo paradigm, confirming that motor responses interfered with the processing of action verbs that involve a movement with the same effector, resulting in slower reaction time. Remarkably, the interference only appeared when the go signal was delivery with a short delay after the verb onset at the early stage of understanding action verbs. Also, the effect was specific for the semantic judgment task and it faded when the Go-NoGo involved a lexical decision task.

In an analogue Go-NoGo task and with the same material used by Sato et al. (2008), Dalla Volta et al. (2009) investigated the kinematic aspect of movement. In the first and second experiment, they reported that the kinematics of manual intransitive and transitive action was slowed down by the auditory presentation of hand-related verbs, but not by the presentation of foot-related verbs. In the third experiment (Dalla Volta et al., 2009), in one condition participants had to respond to hand-related and foot-related verbs with a movement either of their right hand or their right foot. In the compatible condition (responding with the hand, to hand verbs and with the foot, to foot verbs), participants were faster to start the action, while the kinematics of the movement was slower, like in the first and second experiment. These data suggest that the verb-related motor program necessary to understand language meaning initially primed the corresponding effector, although at a later moment meaning interferes with the ongoing motor execution, because both processes compete for motor resources. These results differed from those of Boulenger et al. (2006), that reported an interference between the processing of action verb and the execution of a reaching movement, only at the initial part of the movement. In a lexical decision task, participants were asked to reach and grasp a small object if a real word was displayed on a computer, and to stop the movement if a pseudoword was displayed. The words could be verbs denoting hand, leg and mouth actions and nouns referred to abstract concept or concrete-no manipulable objects. The kinematic analysis revealed that, in an early temporal window, the execution of the motion was slower during the presentation of the action verbs, but not during the presentations of the nouns. Dalla Volta et al., (2009) explained that the difference in the results could be due to the distinct task used in the studies. The authors argue that to fulfil the lexical task (Boulenger et al., 2006), the comprehension of the verb meaning is not necessary, while to accomplish the semantic task (Dalla Volta et al., 2009) understanding meaning, and therefore fully activating the verb features, is required. De Vega et al., (2013) confirmed an interference ACE, investigating for the first time the dissociation between the motor and the semantic processes. Transfer sentences, describing motion away from oneself (“I threw the tennis ball to my rival”) or toward oneself ("My rival threw me the tennis ball"), were displayed divided in segments. When a visual cue appeared during the transfer verb presentation, participants had to realize a movement away from or toward themselves to press a button, and at the end of the trial they had to choose between two alternative words, the one that best completed the sentence. This procedure permitted to explore both the influence of action language on the concurrent motor task and the effect of the motor task on a further semantic completion task. Furthermore, the study aimed to explore the temporal overlap between meaning comprehension and action execution, by manipulating stimulus onset asynchrony that is the temporal delay between the verb appearance and the visual cue. The selected temporal delays were 100, 200 and 350 ms. In line with Boulenger et al., (2006), in the matching condition, when the transfer verb and the movement response had the same direction, interference was found compared to the mismatching condition, but only at shortest delays (100–200 ms). By contrast, a facilitation effect was detected in a largest verb-action delay (350 ms) for the matching condition, indicating priming between meaning and action. The early temporal interference was explained as a competition of the same motor neural resources involved in action sentence comprehension and in the execution of the same action described in the sentence. In accordance with the embodied approach to meaning, the simulation necessary to understand a sentence describing an away transfer motion requires the activation of specific neurons in the motor cortex that are active in planning or execution of action in the same direction, leading to an interference. Moreover, it seems to be the case that the competition for neural motor resources appeared at an early stage of verb processing, in fact when the motion was delayed more than 200 ms the standard facilitation for meaning-action matching conditions was found (de Vega et al., 2013).

In conclusion, these results point out the central role of motor and premotor areas on action-related meaning. Still, behavioral data are not sufficient to directly test the level of involvement of the motor system on language comprehension, since they do not provide any evident measure of brain motor activity. Due to this reason, other studies using fMRI and EEG techniques allowing direct measures of brain activation were conducted.

1.1.2 Neuroimaging evidence of the involvement of the motor system in action-language processing

In the last few years, neuroimaging studies have consolidated the EC view on language meaning, providing important evidence about the central role of the motor brain network in action-language comprehension (Aziz-Zadeh et al., 2006; de Vega et al., 2014; Desai et al., 2010; Kemmerer et al., 2008; Pulvermüller, 2003, 2005; Raposo et al., 2009; Tettamanti et al., 2005; van Dam et al., 2010; Willems et al., 2010). For example, Hauk et al. (2004) asked participants to passively listen action word related to the face, arm or legs (e.g., *to lick*, *to pick* or *to kick*), while their hemodynamic response was registered via fMRI. In another session, the same participants performed a real movement with the same body part involved in the action word previously presented. The result showed a somatotopic activation of the motor and premotor cortex, that is, listening an action word or executing a movement of the motion being described, produced overlapping activations along the motor network (Figure 1.1).

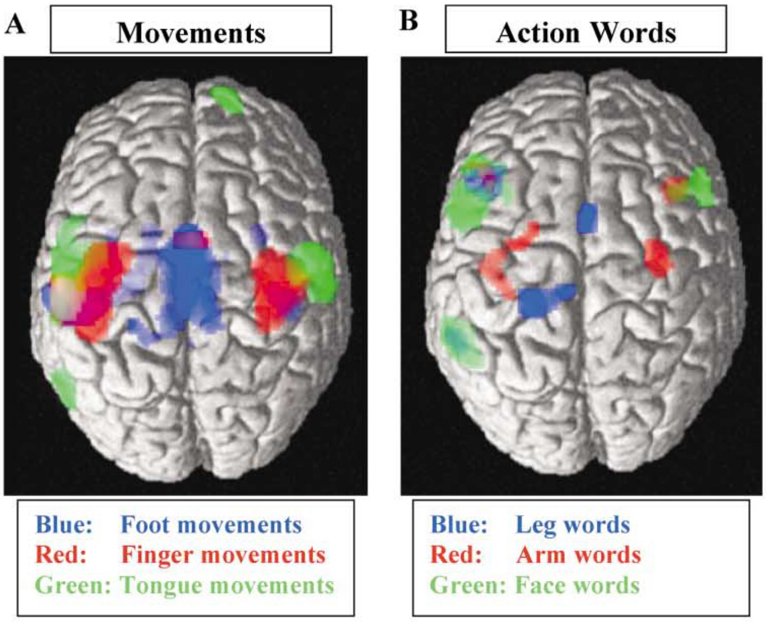

Figure 1.1. (Hauk et al., 2004). A) Hemodynamic activation during foot, finger and tongue execution. B) Hemodynamic activation during leg, arm and face action word comprehension.

The activation of motor areas associated with action verbs presentation was confirmed and deepened by successive investigations. In particular, Kemmerer et al. (2008) evaluated brain activation, while participants performed a semantic judgment task of verbs belonging to five different semantic classes; that is, *action*, *motion*, *contact*, *change of state*, and *tool use*. On their side, the action verbs differed from each other in the amount of implied movement and type of the effector used, thus involving different subcategories. The authors reported somatotopic activation, in primary motor and premotor cortices, for action verbs expressing hand, arm or leg low-intensity movements. Compatibly, van Dam et al. (2010), reported stronger BOLD (*Blood Oxygenation Level Dependent*) signal in motor-related brain area for action verbs denoting specific motor programs than for action verbs denoting a more general program.

The experiments described this far, have focused on the comprehension of isolated word or verb, not included in a linguistic context. Nevertheless, it has been demonstrated that action related sentences also activate motor and premotor brain areas (Aziz-Zadeh et al., 2006; de Vega et al., 2014; Desai et al., 2010; Raposo et al., 2009; Tettamanti et al., 2005). For instance, in the fMRI experiment conducted by Tettamanti et al. (2005), participants were presented with action sentences describing mouth, hand and leg movement and abstract sentences, used as a control condition. The result revealed that listening to action sentences, beyond the type of effectors, led to the activation of a fronto-parieto-temporal circuit, with a common locus in the pars opercularis of the left inferior frontal gyrus, employed also in the action execution and observation process. Additionally, in line with the studies described before, they found a somatotopic activation in premotor region. Similarly, Aziz-Zadeh et al. (2006) showed a congruent effector-specific activation pattern in the left premotor region, when participants observed actions and read sentences both related to foot, mouth or hand movements. Another interesting study performed by Raposo et al. (2009) wanted to investigate whether the involvement of the motor regions on action word processing is automatic or it depends on the context in which is embedded. For this purpose, they presented to participants isolated arm and leg-related verbs (e.g., *kick*), inserted in literal sentences (as in *kick the ball*) and inserted in idiomatic sentences (as in *kick the bucket*). The results revealed that only the isolated verbs and the literal sentences generated activity in motor and premotor cortices, suggesting that the context modulate motor activation.

Further steps in the embodied approach to language were taken by Desai et al. (2010) and by de Vega et al. (2014). The former conducted an fMRI study investigating the neural activity associated with sentences that contained and/harm action, visual and abstract verbs, demonstrating that reading action sentences activated the sensory-motor regions generally involved in planning, execution and perception of those actions, while visual sentences were associated with high-order visual area in the left hemisphere and abstract sentences activated superior temporal and inferior frontal regions. On their side, de Vega et al. (2014) proved that the involvement of motor regions also takes place in action language included in complex discourse referring to hypothetical or no occurring events, such as counterfactual and negated statements. They presented to the participants paragraphs describing action and visual events, in three different syntactic structures: factual (*Given that it was my birthday /* ***I unwrapped the gifts***), counterfactual (*If it had been my birthday /* ***I would have***

unwrapped the gifts) and negation (*Given that it was not my birthday /* ***I didn’ t unwrap the gifts***). Regardless the type of structure statements, action sentences, compared with non-action sentences, induced stronger activation in the supplementary motor area, a region typically associated with the planning and understanding of actions (e.g., the left superior temporal gyrus, the left and the right supramarginal gyri), and in the extrastriate body area which is involved in the visual processing of the body movement. Moreover, not only factual statements, but also counterfactuals and negations led to this pattern of action-related activation, suggesting that even when the action is insert in a hypothetical or negated discourse activate by default brain areas implicated in action comprehension and planning.

Although the neuroanatomical results provided by the fMRI support the embodied view on linguistic meaning, this technique lacks good temporal resolution, making it necessary the use of complementary techniques like MEG, which has both high temporal and relatively good spatial resolution, allowing to accurately evaluate the temporal course of the motor activation in the brain. For this reason, Pulvermüller et al. (2005) recorded brain activity through high-density MEG, when subjects passively listened to action words referring to the face or the leg. An early brain response (between 130-200 ms, see Figure 1.2) was elicited more strongly in the left inferior frontocentral areas during face word processing, whereas, the leg word processing was associated with stronger activity in superior central areas, close to the cortical leg representation, confirming the somatotopic activation seen in the previous studies (Aziz-Zadeh et al., 2006; Kemmerer et al., 2008; Raposo et al., 2009; Willems et al., 2010).

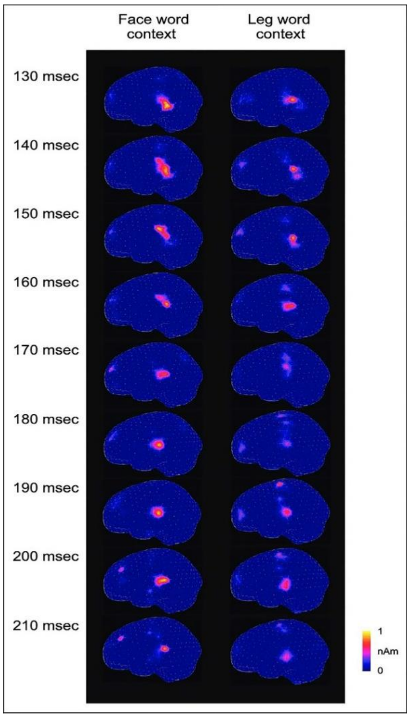

Figure 1.2. (Pulvermüller et al., 2005). Temporal activation of the inferior frontocentral areas for face (left column) and leg (right column) related words.

Similar results were provided by recent MEG studies. Klepp et al. (2014) found early (200 ms) somatotopic activation for hand and foot verbs in neuromagnetic hand and foot source, respectively, that were determined by actual movements performed by the same subjects. Another experiment from the same lab (Klepp et al., 2019), showed how an action verb priming influenced a motor response executed with the same effector implicit in the verb. Behavioral results revealed faster reaction time for the congruent condition, accompanied by reduction of power of motoric brain rhythms over the corresponding region of the sensorimotor area, which is assumed to be a reflection of facilitated processing typically observed in semantic and motor-language priming (Henson & Rugg, 2003; Mollo et al., 2016). Specifically, hand verb primes induced reduction of alpha power suppression in hand motor region, and compatibly, foot verb reduced alpha/beta power suppression in foot sensory area.

To summarize, neuroimaging studies give remarkable information about the role played by the sensory-motor system during the comprehension of action language. Still, as mentioned above, fMRI suffer of poor temporal resolution and it can provide only indirect measure about the process associated with the BOLD signal, although the MEG overcomes this problem. In the next section we will consider the EEG, which boasts an excellent temporal resolution (millisecond), allowing to efficiently evaluate the temporal course of motor processes during action language understanding, and is a much cheaper and flexible technique than MEG. Also, it can offer details about the cerebral sources that generate the EEG modulation associated with the comprehension.

1.1.3 Temporal dynamics of motor activation coming from EEG studies

A considerable number of EEG studies investigated the electrical brain response, such as the event related potentials (ERPs), associated with action language comprehension (Dalla Volta et al., 2014; Olaf Hauk & Pulvermüller, 2004; Moreno et al., 2013, 2015; Pulvermüller et al., 2001; van Elk et al., 2010). Most of them investigate the spatiotemporal dynamics during the process of action words and sentences and some try to confirm that actions verbs referred to different effectors are topographically represented in the motor cortex, as reported by fMRI (Olaf Hauk et al., 2004; Kemmerer et al., 2008; Klepp et al., 2014; Pulvermüller, Shtyrov, et al., 2005; Tettamanti et al., 2005). For example, it has been shown that reading action word related to the face, the leg or the arm elicit topographical differences in frontal brain activity between 220 and 250 ms (Olaf Hauk & Pulvermüller, 2004; Pulvermüller et al., 2001). In particular, the leg-related words produced stronger activation in brain areas around the vertex, near to the cortical representation of the leg, and the face-related words activated the inferior-frontal brain areas in the left hemisphere. In these studies, pseudo-words or non-linguistic stimuli were used as control conditions. On their side, Dalla Volta et al. (2014) were interested in evaluating the spatiotemporal dynamics of sensory-motor areas for action verbs versus abstract verbs. Participants performed a semantic decision task involving verbs describing foot, hand and mouth actions and verbs with an abstract content. The ERPs analysis showed more negative amplitude associated with action related language relative to abstract language at both early (at around 270 ms) and late (300-400 ms) time interval. Depending on the type of effector implicit in the verb, the topographic distribution for concrete action verbs included specific parieto-frontal motor regions. On the contrary, the EEG source analysis effect for the abstract verb revealed activation in pre-frontal areas outside of the sensory-motor network. Taking together, these results confirmed that concrete action words recruit sensory-motor regions, which are organized in a somatotopic way according to the effector described by the verb, supporting the EC idea of a crucial link between the sensory-motor system and action language comprehension.

Another aspect of the EC approach to language that is still under debate, is whether the motor activation associated with language process reflects an automatic retrieval of the lexical-semantic features (Pulvermüller, 2005) or a post-lexical motor imagery (Toni et al., 2008). To elucidate the question, van Elk et al. (2010) selected action verbs that could refer to actions performed by both human or animals (e.g., human context: *The athlete jumps over the hurdle;* animal context: *The deer jumps over the fence*). Both types of sentences involved the same number of words, but the kinematic of the action was clearly different. The authors hypothesized that if motor brain activity associated with language processing reflects motor imagery, the EEG should indicate stronger motor activation for human sentences compared to animal sentences, since the motor imagery for human context should be much easier that motor imagery for animal action. On the contrary, if motor brain activity associated with language processing is due to the retrieval of lexical-semantic information, then reading sentences in the animal context would lead to stronger activation in motor region compared to human sentences. The results support this latter hypothesis, showing larger mu and beta frequency rhythm desynchronization for the action verbs inserted in animal contexts than in human contexts, especially in frontal-central scalp regions. Although this pattern could be counterintuitive, because one should expect larger motor resonance for human actions, included in our motor repertoire, a possible reason provided by the authors is that action sentences had higher cloze probability of noun-verb pair in an animal context compared to a human context. For example, a verb like “jump” is more easily predictable when the agent of the action is an animal than a human. It should be noted that the EEG desynchronization was significative different between the conditions at a relative early temporal interval (200-600 ms), further corroborating the assumption that language-induced motor activation is automatic and, therefore, it reflects the retrieval of lexical-semantic information associated with the verbs. The major novelty of the study is that for the first time the processing of action language was associated with the desynchronization of mu and beta rhythm, typically observed during action execution, action observation and motor imagery. However, the study presents a substantial limitation, that is, the absence of a strong control condition like no-action sentences. Therefore, it cannot be concluded that the mu and beta desynchronization was specific for action language comprehension.

In order to answer this question, Moreno et al. (2013) investigate whether mu and beta rhythm modulation is restricted to action language or it is expanded to language processing in general. Additionally, they aimed to contrast action language with the observation of real actions, to verify that mu and beta suppression was similar for both conditions. To these purposes, participants had to listen action sentences (*Now I cut the bread*) and abstract sentences (*Now I doubt of the plan*), or they had to watch action videos while their EEG was recorded from mu and beta analysis. The spectral analysis showed a suppression of mu oscillatory rhythms for both action observation and action-related language in central electrodes, and no change was seen for abstract sentences. Figure 1.3

depicts the topographies of oscillatory rhythm in the frequency bands of mu (8-13 Hz), showing that both action observation and action language exhibited stronger mu power suppression than abstract language, whereas no differences was found between action language and action observation.

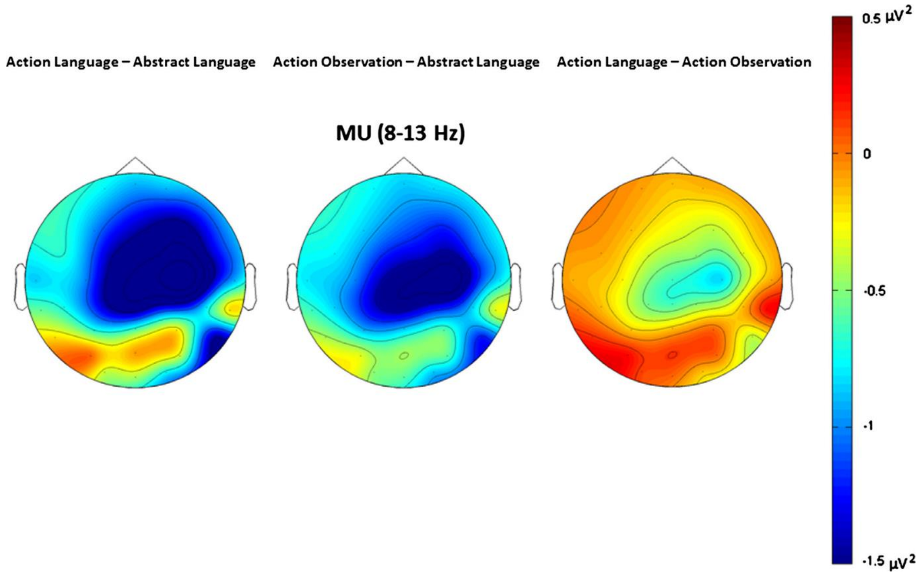

Figure 1.3. (Moreno et al., 2013). Topographic distribution of the mu oscillatory rhythm. The subtractions of the mean EEG power between Action language and Abstract language (leftward plot) and between Action observation and Abstract language (central plot), showed mu suppression (negative values in the scale) in both action conditions. On the contrary, the difference between Action language and Action observation (rightward plot) do not present any significative difference in mu oscillatory band.

A subsequent study from the same laboratory (Moreno et al., 2015) intended to go one step further, analysing the time frequency of mu rhythms when participants were reading action sentences (*You will open the door of the room*), perceptive sentences (*You will hear the teacher's command*) and abstract sentences (*You will doubt the patient's dialog*). The time frequency analysis revealed fronto-central mu suppression for action sentences, but no for perceptive and abstract sentences, while participants were reading the first noun (contrast action vs abstract) or the second noun (contrast action vs perceptive), suggesting that the lexical-semantic integration drives the activation in motor-related regions. Even so, it should be noted that the linguistic materials involved action verb corresponding to generic action, which implemented different motor programs depending on the object they refer, forcing the reader to continue to obtain enough information. Then, if a verb conveys a specific motor program it could be sufficient to activate motor areas.

Other interesting studies evaluated motor and semantic processes indexed by ERPs by means of motor-compatibility effect. For instance, using an ACE paradigm, Aravena et al. (2010) presented to the subjects, sentences expressing actions performed with open hand (*The show was praiseworthy, so Rocio* ***applauded***), actions performed with close hand (*He needed to drive the nail correctly, so Joseph* ***hammered*** *it*) and no-action (*After waiting a long time to see his grandmother, Amaro* ***visited*** *her*). After listening the sentence, participants had to press a button using a pre-assigned hand-shape; half of them were instructed to press the button with their hand open, the other half with the hand close. Consequently, the hand-shape could match or mismatch the action described in the sentences. The results revealed that the mismatching condition enhanced an N400-like component (a large negative deflection in the ERP that takes place 400 ms after word presentation) in the CZ electrode, and also reduced the amplitude of early and late markers of motor process. In sum, the authors not only replicate the ACE at cerebral level, reporting that motor incompatibility induced a semantic interference effect (as reflected by N400), but they also demonstrated a motor interference effect; that is, there was a bidirectional relationship between the action execution and semantic comprehension processes. On the other hand, Santana & de Vega, (2013) using a purely linguistic task, manipulated the temporal compatibility of two manual actions, performed by a protagonist either simultaneously (*While cleaning the wound/he unrolled the bandage*) or consecutively (*After cleaning the wound/he unrolled the bandage*). Whether the actions were simultaneous or consecutive, determined the incompatibility or compatibility of the sentences, respectively. The ERPs analyses, which were recorded from the verb and the noun of the second sentence, reported larger N400 amplitude, only for the noun, in the incompatible condition compared to the compatible one, reflecting motor compatibility effect. This result brings the authors to conclude that to judge an action feasible or not, is necessary to integrate all the semantic information gathered in the sentence. Additionally, to exclude the possibility that the adverb itself (*while* vs *after*) could induced the pattern of N400 modulation, in a second experiment, the authors presented only *while* sentences and manipulated the congruence dependent on the motor contents. That is, all the periods started with the adverb while, but in the compatible condition the first action was perceptive and the second one was motor (*While looking at the wound/he unrolled the bandage*), while in the incompatible condition both sentences described manual actions (*While cleaning the wound/he unrolled the bandage*). The results, showed again an enhancement of N400 component associated with the incompatible condition only for the noun following the verb in the second sentence, confirming that it is necessary the accomplished semantic process of the sentence (up to the noun), to detect the motor incompatibility. This could be one of the cases, as discussed above, where the verb itself is not able to represent the motor properties of the action since it is too indeterminate, then the association with a noun is needed. This result suggest that motor representations are context-depend, rather than triggered by the verb contained in the sentence.

From the studies described in this section, four main conclusions can be drawn about the role of motor processes in the comprehension of action language: (1) The motor activation associated with action language has a somatotopic distribution and occurs at an early temporal window (~ 200 ms after word presentation) (Dalla Volta et al., 2014; Olaf Hauk & Pulvermüller, 2004; Pulvermüller et al., 2001); (2) such action-language activation appears to be automatic (van Elk et al., 2010); (3) the comprehension of action-language induces a suppression of mu and beta rhythms, which are neurophysiological marker of motor processes, similar to what occurs during action execution, action observation or action imagery (Moreno et al., 2013, 2015; van Elk et al., 2010); (4) there is a mutual influence between performing actions and simultaneously understanding action language (Aravena et al., 2010; Santana & de Vega, 2013).

Despite the important contribution of the EEG studies in revealing the temporal dynamics of the motor brain during action language processing, they cannot explain whether the motor brain activity is really necessary to comprehend action words or sentences. One way to assess this issue, is by using "causal" methodologies, that we will thoroughly discuss in the next paragraph.

1.2 Supporting the causal role of motor activation in action-related language understanding: non-invasive brain stimulation evidence

With the term non-invasive brain stimulation, we refer to those techniques which induce a temporary and reversible modulation of the neural excitability in specific brain areas via transcranial stimulation. From the last few decades, these techniques have been extensively used in healthy adults to investigate brain mechanism or to modify and enhance cognitive, behavioral, social and emotional process, since they offer both high spatial and high temporal resolution. Two major techniques among the non-invasive brain stimulation are Transcranial Magnetic Stimulation (TMS) and tDCS.

The TMS consists of inducing a brief, strong and focal magnetic field to the human scalp by means of a stimulation coil. The magnetic field generates a depolarization and/or a hyperpolarization of the neural population in the underlying region (Jahanshahi & Rothwell, 2000; Pascual-Leone et al., 2000), interfering with the neural computation being perform. Such TMS-induced perturbation results in behavioral or physiological changes, as reflected by reaction times and errors measures, or motor by evoked potentials, making this techniques an extremely useful tool to investigate the causal role of a specific brain region on a determinate cognitive function (Pascual-Leone et al., 1999; Walsh & Rushworth, 1999).

The tDCS induces weak electrical current through the scalp between two electrodes, changing the threshold of discharge of stimulated neurons (Fritsch et al., 2010; Nitsche, Nitsche, et al., 2003; Nitsche & Paulus, 2000, 2001), inducing a long-lasting and profound excitability aftereffect. Unlike TMS, tDCS is not able to induce action potentials since the current generates a subthreshold electrical field in the brain that modify neural transmembrane potential. Specifically, depolarizing the cellular membrane induce long-term potentiation while the hyperpolarization result in long-term depression.

For both techniques, it is fundamental to choose the appropriate stimulation protocol to correctly evaluate the influence of a given area on a given task. Regarding TMS, several parameters like stimulation intensity, timing, location, type of coil, coil orientation, etc. need to be considered. Instead, tDCS effects depend on the electrodes' location, current intensity, duration, electrode size, electric field orientation and so on.

Still, the TMS and tDCS are particularly useful and suited to deal with the "causality issue", namely, to what extent cortical motor activation is necessary for language processing. Then, the next subsections, will present studies involving TMS and tDCS to assess whether M1 is actually crucial for processing action-related language, dividing them according to the chose stimulation protocol.

1.2.1 **The functional link between motor activation and action-related language: single pulse TMS**

Depending on the type of stimulation selected, non-invasive brain stimulation techniques allow to evaluate different level of contribution of a given area to the specific function of interest. Among others, single-pulse TMS (spTMS), can be used to study the physiological and behavioral effect of online stimulation of the motor system. At physiological level, when spTMS is applied over the M1, it induces MEP in the peripheral muscle, providing a direct measure of the corticospinal excitability (CSE) with high temporal resolution. When a language task modulates MEPs in a motor brain region it is a reflection of the functional link between the task and the motor area.

Several studies employed spTMS to test the activation of M1 during the processing of action-related language, focusing on evaluate behavioral (Pulvermüller, Hauk, et al., 2005; Tomasino et al., 2008) or physiological (Buccino et al., 2005; Candidi et al., 2010; Innocenti et al., 2014; Papeo et al., 2009) measures. For example, Pulvermüller, Hauk, et al. (2005) delivered spTMS over left language motor areas during a lexical decision task. Hand or leg action-related words, together with distractor and pseudowords, were presented to the subjects who had to respond as fast and accurately as possible when a word was meaningful, by a brisk lip movement. In different blocks, subthreshold TMS pulses over the hand or leg motor area were delivered after 150 ms of word onset. Additionally, to exclude any possible effect independent from the stimulation, two control experiments with sham TMS (no stimulation) and active TMS applied over the right hemisphere were run. The analysis on reaction time showed that participants were faster to judge arm words, compared to leg words, when the hand area was stimulated, and the reverse effect was found for the leg area stimulation. No effect was found in the two control experiments. The authors demonstrate that motor areas of the left hemisphere are specifically involved in processing action words of different semantic categories, revealing a functional link between the action and the language system. According to the EC view, the relationship between motor activation and action language processing reflects the motor simulation of the semantic meaning expressed by the word or the sentences. Tomasino et al. (2008), aimed to verify in the same experiment whether such simulation is implicitly trigger during passive reading task as well as during a motor imagery task. The study included hand-action related verbs, that participants were instructed to read while performing three different tasks: reading task (“Silently read the verb”), motor imagery task (“Imagine yourself performing the action”) and frequency judgment task (“Is this a word you would frequently read in newspapers?”). Subthreshold TMS pulses was delivered over the left hand representation in M1 or over the vertex, serving as a control, at different time point from stimulus onset (150, 300, 450, 600 or 750 ms). The main finding concerns the facilitatory effect in the reaction time for the hand action verbs, induced by the TMS over M1, specific in the imagery task only. Additionally, the facilitation was observed at early delay (150 ms), suggesting that motor simulation occurred very fast. In conclusion, these results suggest that the motor simulation of the hand action implemented during reading, is associated with neural motor activation. In a similar way, Papeo et al. (2009) investigated whether action words automatically elicit motor activation, even when the task does not require the explicit retrieval of sensorimotor information, or whether motor activation only occurs when the task critically demands this retrieval. An additional objective of the study was to identify at which stage of the word process (early lexical-semantic stage, late lexical-semantic stage and post-conceptual stage), the motor activation occurred. In three experiments, which differed only in the timing of stimulation, participants were presented with hand-action, no-hand action and non-action words while they performed either a semantic or a syllabic judgment task. In the first task the participants were asked to evaluate the content of the verb (physical act or mental state), while in the second task they had to indicate the number of the syllables for each verb. The spTMS pulses were triggered at 170 ms, 350 ms and 500 ms post-stimulus over M1 corresponding to the right first dorsal interosseous (FDI) muscle of the right hand with an intensity of 120% of the rest motor threshold (rMT). Analysis on MEPs amplitude showed that only in the post-conceptual stage of hand-action word processing (500 ms) the TMS enhanced and decrease M1 activity in the semantic task and in the syllabic task, respectively. In the no-hand action and non-action condition, no effect of the TMS was detected. According to the authors, these results indicate that rather than playing a functional role in action language, the activation of the motor system follows the understanding process. In contrast, Buccino et al. (2005), found a TMS-induced modulation of motor cortex excitability, which occurred quite early after verb presentation. In detail, participants listened to sentences expressing hand or foot action movement and abstract sentences while spTMS was applied to the hand or foot motor area in the left hemisphere. The supra-threshold pulses were delivered when the second syllable of the verb was presented. Unexpectedly, as depicted in Figure 1.4, the stimulation of hand area induced a decrease in CSE associated with hand-action sentences, and, complementary, the MEPs amplitude for foot action verbs was smaller than the other conditions when TMS was deliver over the foot motor area.

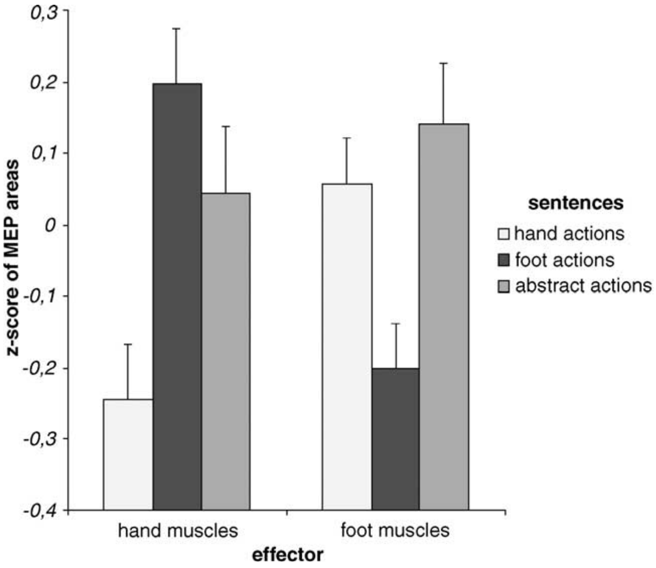

Figure 1.4. (Buccino et al., 2005). Mean values of MEPs amplitude for hand and foot area, after listening hand-action, foot-action or abstract sentences.

The main result of the study is the somatotopic activation of the motor area corresponding to the effector involved in the action sentences, which suggest a modulation of the motor representation of the action being described. Moreover, listening to abstract sentences did not produce any change in brain motor activity. Still, one would have expected a facilitatory modulation of the motor activity, that is, an increase of MEPs amplitude, rather than a decrease. However, there were two important differences between this study and the ones described above (Papeo et al., 2009; Pulvermüller, Hauk, et al., 2005). First, the modality of presentation of language materials; Buccino et al. (2005) used a passive listening task, rather than a reading task. Second, the timing was different; TMS pulses were delivered very soon during the second syllable of the verb, while in the other experiments the TMS was applied at 150 ms of verb presentation (Pulvermüller, Hauk, et al., 2005), or even at later delay (Papeo et al., 2009).

In this respect, another recent study (Innocenti et al., 2014) attempted to determine the direction of language-related motor activity (increase or decrease), to individuate at which stage of verb recognition such activation occur and, as novelty, to test whether the repetition of the verb would decay the activation of M1. After the presentation of hand-action-related and abstract verbs, participants were asked to recognize the content of the verb (action-related or abstract). The experiment consisted of two identical blocks. The TMS was applied over the left M1, to induce MEPs in the right FDI, at 300 ms or 500 ms after the stimulus presentation, then each verb was presented twice within each block. The results evidenced an early motor activation (300 ms), as expressed by the increment of CSE, specific for the action verb processing, but no for the abstract verb, only in the first block. In contrast, no significant difference was revealed in the second block. This pattern of activation permitted the authors to conclude that action language understanding, at least at an initial phase, takes advantage of motor simulation to access the semantic meaning of the verb, but this motor simulation does not seem necessary after the repetition of the verb. Finally, Candidi et al. (2010) explored another aspect of the link between motor areas and the action-related language representations, that is, whether motor simulation, generated by the action content, can be influenced by the tense (past vs future) of the verb. The linguistic material consisted of verbs referring to hand-action or leg-action, sensorial non-somatic verbs and abstract verbs conjugated in both past and future tense. The verbs were visually presented to the subjects, and the MEPs were recorded from the hand and leg representations in the left M1. TMS was randomly applied between 500-700 ms after the verb presentation, at an intensity of 120 % of the rMT. The only significant contrast was for hand-action verbs, which elicited higher MEPs in the future tense compared to the past tense, indicating a sort of "motor readiness" driven by future tense verbs. Such motor facilitation is explained by the effect of an anticipatory simulation, similar to the one observed during motor action observation (Urgesi et al., 2006, 2010).

Overall, the spTMS results discussed so far, provide considerable evidence that M1 activity is modulated by the process of action-related words and sentences, despite the inconsistency on the direction of the motor activation (decrease vs increase). However, these findings are still insufficient to argue that the modulation of motor brain activity is functional for the comprehension. In fact, as mentioned before, we need a paradigm that can provide a quantitative evidence of the involvement of the motor system in semantic understanding.

1.2.2 **Disruption of motor activation by means of repetitive TMS during language comprehension**

The rTMS allows to selectively manipulate the activity of brain regions of interest, such as the motor or premotor cortex, in healthy participants to evaluate their functional contribution to the comprehension of action language. When the rate of the repetitive pulses is higher than 1Hz, the so called "high-frequency" rTMS, the stimulation can induce an increase of neuronal excitability. On the contrary, "low-frequency" rTMS (stimulation rate equal or less than 1Hz) can induce a decrease of neural activity.

In cognitive neuroscience low-frequency rTMS is often used to temporally disrupt the function of a given cortical region, creating the so-called "virtual lesion", to evaluate the behavioral consequences. In particular, in some studies, the activity of the motor cortex in healthy participants was disturbed by means of rTMS, to assess its causal role in the understanding of action-related language (Gerfo et al., 2008; Kuipers et al., 2013; Repetto et al., 2013; Vukovic et al., 2017; Willems et al., 2010). Gerfo et al. (2008) applied rTMS to test whether the motor cortex is causally implicated in both the process of grammatical and semantic representation, or if it is required only for the semantic knowledge. Since the premotor cortex seems to be involved in the process of grammatical class of verbs and M1 in the semantics of action verbs, in two experiments, participants received sham and active low-frequency rTMS over the left prefrontal cortex (Exp1) or over left M1 (Exp2) before performing a morphological task with state and action words. The stimuli consisted of action verbs (i.e., *to grasp*) and state verbs (i.e., *to doubt*) presented in the first person singular of the indicative mode, or nouns referring to manipulable objects (i.e. *the pen*) or to abstract concepts (i.e. *the beauty*). After the presentation of each stimulus word, a symbolic cue appeared, indicating the participants to produce aloud, the first person of singular or the third person singular when the stimulus word was a verb, or to produce the singular or plural form if the target word was a noun. The response latency showed that active rTMS over left M1 increased the reaction time in the production of both action verbs and action nouns, compared to the production of state verbs and abstract nouns. Moreover, the active rTMS on the prefrontal cortex reduced the performance only for the action verb. In other words, both frontal areas underpin the processing of action language, however, M1 plays a specific role in the semantic representation of action words, while the prefrontal region is involved in both grammatical and semantic aspect of word processing. Similarly, Repetto et al. (2013), used the virtual lesion approach to address the causality of motor cortex activation in the comprehension of semantic characteristics of the action language. Before a semantic comprehension task, containing manual action verb and abstract verb, sham and active low-frequency rTMS was delivered over left or right M1 of right-handed healthy humans. As revealed by the reduction in the performance specific for the action verbs only after left M1 stimulation, it can be claimed that the motor area subserves the action verb process in a functional manner. Another interesting aspect to consider, is the specificity of the hemisphere stimulated, that is, in right-handed participants, only the perturbation of left M1 activity affects the semantic process of the verb. An interesting study (Kuipers et al., 2013) combined rTMS and ERPs techniques to evaluate the contribution of M1 in the semantic process of bodily action words. Pairs of verbs expressing hand-related or mouth-related movement were visually presented to the subjects. The critical conditions were hand-hand pairs and mouth-mouth pairs, while the mixed pairs were used as filler and then excluded from the analysis. The innovative aspect of this experiment is that the low-frequency sham and active rTMS was applied over the right hand-area, namely over the left M1, during the presentation of the first verb (prime verb), which induced an online perturbation. The semantic relationship between the prime verb and the target verb (second verb) was measured by the N400 amplitude, a reliable index of the semantic prime. The N400 amplitude, recorded from the target verb, after active rTMS was higher for the hand-hand action pairs compared to sham rTMS, while no changes in the ERPs signal were detected for the mouth-mouth condition. This pattern of activation indicates that the disruption of neural activation of the hand-motor region led to a specific reduction of the semantic priming between the hand-action verbs, confirming the EC view of a substantial role of M1 in meaning comprehension. Two major points of the study should be emphasized; first, unlike previous studies, the task did not require any response preparation and the paradigm used was a semantic paradigm; second, the N400 modulation prove a pure measure of the semantic processing.

An efficient variant among the rTMS protocols, allowing a more rapid and long-lasting effect on neuroplasticity, is the Theta Burst Stimulation (TBS). As we will see in chapter 3, TBS can induce long after-effect with a stimulation time between 20 seconds and 3 minutes (<10% of the time required by conventional rTMS), delivering higher-frequency (50 Hz) train of 3 pulses every 200 ms. The pulses can be given continuously and intermittently, producing, respectively, a long lasting inhibitory or excitatory effect on the underlying cortex.

Due to this reason Willems et al. (2011) used TBS protocol to investigate the role of premotor cortex on a language-processing task. Offline TBS (before the task) was applied over the right or the left hand motor area in the premotor cortex, in right-handed participants. After the stimulation, participants were instructed to judge whether manual-action verbs, state verbs and pseudowords presented on a screen were an English word or not. Analysis on RT revealed that TBS over the left premotor cortex improved time response for manual-action verbs compared to the state verbs and the pseudowords, additionally, no changes induced by TBS on right premotor cortex were found. This finding confirms the functional links between motor areas activity and action language comprehension, suggesting a body-specific activation of the premotor cortex for the effector involved in the action verb. Still, one would have expected an inhibitory effect on task performance after the disruption of premotor activity. According to the authors, since it is not clear how the stimulation acts at behavioural level, it is possible that the TBS-induced inhibition at the neural level resulted in a behaviourally facilitation. Finally, Vukovic et al. (2017) investigated the causal role of M1 in action-semantic aspects of meaning, by means of a rTMS similar to TBS protocol. They contrasted the RT resulting from a concreteness judgment task and lexical decision task involving hand action words, abstract words and pseudowords. They used an online interference TMS protocol (20 Hz burst of 4 pulses) over the hand motor area in M1 in both left and right (serving as control) hemisphere that was delivered at the onset of the word and lasted for 200 ms. The result showed that rTMS over the left M1 induced slower RT for action words than for abstract words in the concreteness judgment task, while the disruption of right M1 activity does not lead to any significative change. Moreover, such results were not found for the lexical decision task, indicating that M1 activation of M1 has indeed a functional relevance in the process of semantic action-related features of language.

1.2.3 The effect of transcranial direct current stimulation over motor areas in action language processing

The tDCS is another non-invasive brain stimulation technique that can induce neuroplastic changes in human cortex for up to a few hours after stimulation. As mentioned before, tDCS can increase neuronal excitability under the anodal electrode, while it can decrease it under the cathodal one. Then, comparing to the TMS, the tDCS afford to test the complementary inhibitory and excitatory effect of the stimulation, by hyperpolarizing and depolarizing the cellular membrane.

Recent studies, aimed to verify whether the motor system is an essential part of the network for action-related language understanding, by means of tDCS techniques (Gijssels et al., 2018; Liuzzi et al., 2010; Niccolai et al., 2017). Gijssels et al. (2018), used tDCS to investigate the opposite effects of anodal tDCS (a-tDCS) and cathodal tDCS (c-tDCS) on the left premotor cortex, in the comprehension of action verbs. Right-handed healthy subjects performed a lexical-decision task, involving unimanual and abstract verbs, with either their right or left hand after receiving facilitatory or inhibitory stimulation. In the facilitatory condition the anodal electrode was placed over the left premotor cortex and the cathodal electrode was placed in the premotor cortex contralateral, allowing, respectively, to excite and simultaneously to inhibit the two premotor areas. In the inhibitory condition the electrode position was reversed, inducing the inhibition in the left premotor area and facilitating the activity in the right one. The analysis on response accuracy, revealed that in the inhibitory condition, the performance was better for the unimanual verbs compared to the abstract verbs. On the contrary, a-tDCS over the left premotor cortex induced more errors for the unimanual verbs than to abstract verbs. The “paradoxical” improvement caused by the inhibitory tDCS over the left premotor cortex is in line with the results found by Willems et al. (2011). Additionally, the facilitation of the same area leads to a complementary “paradoxical” worse performance. The authors speculate that this pattern of result reflects the competition of similar simulations partially activated by an action verb. The a-tDCS on the left premotor area may increase the activation of competitive simulations, leading to an impairment in the performance, conversely, the inhibitory stimulation may decrease such competition, facilitating the behavioral response. Similarly, Niccolai et al. (2017), intended to shed new light on the direction-effect issue, by exploring the consequences of tDCS modulation on the verbal-motor interface, and thus assessing the causal role of the motor system in language understanding. Specifically, the authors aimed to examine both the tDCS-induced effect of M1 on verb comprehension and the effect of a deep semantic processing on the stimulation, by means of a double dissociation task based on a Go-NoGo paradigm. Hand-action verbs, foot-action verbs and abstract verbs were presented to the participants, that were asked to judge whether the verbs were concrete or abstract. In case of a concrete verbs (Go trial), a visual cue indicated that subject had to response either with their right hand or their right foot. Each participant received in different days online anodal, cathodal and sham tDCS over the hand-area in left M1, for the entire duration of the task. Analysis on the response times of the semantic discrimination task, c-tDCS induce faster responses for hand-action verbs independently of the type of effector used to produce the answer. No similar effect was found neither for foot-action verbs nor for a-tDCS. According to the authors, the facilitation observed for c-tDCS could reflect the inhibition of M1 for both hand-verb processing and hand response preparation. In other words, the activity in M1 generated by the comprehension of hand-verb and the motor preparation to perform is decrease by cathodal stimulation, reducing the interference between them, and consequently resulting in faster response.

Although the direction of the effects of both studies was unexpected, it was clear that the modulation of hand premotor area affects the processing of manual action verbs, suggesting that the simulation causally contributes to the comprehension of the action-language meaning.

A specific inhibitory effect in a linguistic task, after applying c-tDCS over M1 was reported by Liuzzi et al. (2010). In this innovative study, they evaluated how the tDCS on left M1 affects the associative learning of novel action related words. In four different days, right-handed participant received anodal, cathodal or sham tDCS, before a training session where they learned the action-related meaning of pseudowords associated with photos of concrete body-related actions. At the end of the fourth training session, the subjects were asked to translate the novel action words into the corresponding German translation. The results showed that when c-tDCS was delivered on M1 the number of correct translations were significatively reduced compared to sham stimulation, while no effect was seen for a-tDCS. Additionally, to exclude the possibility that the stimulation could affect prefrontal regions near to M1, another experiment was conducted with the tDCS applied over the left dorsolateral prefrontal cortex instead of M1. Even in this case, no effect on the number of translations was reported. The novelty of this study regards the causal role performed by M1 in the acquisition of novel action-related words.

1.3 Conclusion

The evidence presented so far clearly shows that processing action language meaning recruits motor areas. In particular, fMRI neuroanatomical data demonstrated motor activation that is somatotopically distributed according to the different effector used in the action described by sentences (see Jirak et al., 2010 for a review). On their side, the electrophysiological studies provide evidence that such activation occur at an early stage of linguistic comprehension, implicating that the involvement of the motor system in action language is fast and automatic.

Overall, these data support an embodied view of linguistic meaning according to which language is grounded in the sensory motor system, but they can also be in part explained by other theoretical approaches which deny the functional role of embodiment cognition. According to this sceptical perspective, the neuroscience data on the relationship between sensorimotor activation and language processing are for most correlational rather than causal; therefore, it is possible that the motor simulations are only a down-stream consequence of the “real” semantic processes (Papeo et al., 2015) which do not contribute to the comprehension of linguistic meaning (Chatterjee, 2010; Mahon, 2015; Mahon & Caramazza, 2008).

In contrast, the non-invasive brain stimulation studies, discussed above, examine the functional link between motor and action-language processes and confirm that the modulation of motor brain region activity influences the performance in action-language tasks. These results refute the idea that the motor activity is just an epiphenomenal spreading activation post-semantic effect, claiming that motor and premotor cortices causally underpin the understanding of the meaning expressed by words or sentences.

Chapter 2:

Processing of sentential negation

All languages contain a repertoire of "function words", like article, preposition, conjunctions and so on. These words are abstract syntactic operators, which require a linguistic context. One type of these unique words corresponds to negations, exemplify by the sentential operator "*no*" or "*not*". Only the human beings possess the capacity to convey characteristic information by means of negative utterances, e.g., expressing rejection, absence, dissent, opposition, irony (Horn, 2001). Through negation, it is possible to communicate what is "not" the case, which sometimes is more useful than communicating what is the case. Although linguistics and philosophy have shown great interest on negation (see Horn, 1989 for a review), the topic has received relatively little attention from psycholinguistics and cognitive neuroscience.

From an embodiment perspective, as we largely described in the previous chapter, language comprehension relies on the sensorimotor mental simulation of the state of affairs referred to by the linguistic content. In other words, to access the semantic meaning, the comprehenders generate a representation of the described events, similar to the representation constructed when directly experiencing the events. Within this framework, sentential negation demands more consideration, since it constitutes a challenge to embodiment: is it possible to create an embodied representation of a negated situation?

From the psycholinguistic study of sentential negation, two predominant models of negation have emerged. On one hand, some psycholinguists suggested that the elaboration of negative statements require more brain resources since they are syntactically more difficult than affirmative sentences (Carpenter et al., 1999; Carpenter & Just, 1975; Clark & Chase, 1972; Just & Carpenter, 1971). On the other hand, other researchers assume that negation reduces the accessibility to the conceptual representation of the negated concepts (de Vega et al., 2016; Kaup, 2001; Kaup & Zwaan, 2003; MacDonald & Just, 1989; Papeo et al., 2016; Tettamanti et al., 2008). Evidence supporting the first model comes from classical studies that used sentence-verification tasks or sentence-picture matching tasks. For example, Just & Carpenter (1971) presented to the subjects an array of black or red dots, and, right after, a sentence like "*The dots are red*" or "*The dots aren't red*" appeared. The subjects were asked to evaluate whether the sentence was true or false, concerning the colours of the dots. The response times revealed that participants were faster to respond in a true condition (red dots paired with "*The dots are red"*) compared to the false condition (black dots paired with "*The dots are red"*) for the affirmative sentences, on the contrary, when the sentence was negative, reaction times were faster for the false condition (red dots paired with "*The dots aren't red"*) compared to the true one (black dots paired with "*The dots aren't red"*). A possible explanation of such result relies on the number of internal operations required in the comparison of sentence and picture representations, what makes faster true – (red dots) & (red dots) - than false affirmative statements – (black dots) &

(red dots). In the case of negative sentences "*The dots aren't red"*, the verification is slower because the representation consists of an embedded preposition - [false (red dots)]- which needs a previous transformation: [false (red dots)]→ (black dots) before the comparison with the picture representation – (black dots).

If understanding negation is cognitively more demanding than understanding affirmation, then one should expect an increment of brain activity during the comprehension of negative sentences compared to affirmative sentences. A pioneering neuroimaging study conducted by Carpenter et al. (1999), which involved a sentence picture matching task, demonstrated that negative language understanding results in greater activation, relative to their affirmative counterpart, of left posterior temporal gyrus (typically associated with language comprehension) and of both left and right parietal region (usually recruited for visuospatial processing). Such pattern of activation was also accompanied by longer response times for negative sentences, compared to affirmative ones. More recently, Christensen (2009), using a similar paradigm in Danish, confirmed the increment of activity in the left premotor area for negative relative to affirmative sentences. In addition, Bahlmann et al. (2011) investigated the different degrees of difficulty in processing negative sentences, using single and double negations. The hemodynamic response showed strong functional activity in the left inferior frontal gyrus, the anterior portion of Broca's area, and in the left inferior parietal lobule for sentences containing the negation in the main proposition, reflecting the higher demand of additional computation to integrate the semantic information needed by the sentential negation.

The second model of negation proposed that negation differs from affirmation because the representation of the negated items is less accessible. This proposal is based on studies which tested the effect of negation using low-level processing measures, such as word recognition or priming paradigms. MacDonald & Just (1989) aimed to investigate the changes in the representation of the negated concept during its process, tested with a probe-recognition task consisting in the presentation of affirmative and negative sentences followed by a word (probe) that participants must judge whether it was mentioned or not in the sentence. The rationale is that affirmative sentences activate the referred concepts, facilitating the recognition of the probe (priming) and shortening its response time, whereas negative sentences would reduce the activation of the negated concept, and therefore the response to the probe would be slower. The authors confirmed this prediction. However, as Kaup (2001) argues, it is possible that the result reported by MacDonald & Just (1989) do not reflect the effect of negation per se, but rather is the consequence of the presence or absence of the concept in the situation model. That is, the affirmed concept is present in the situation model, while the negated concept is not. Thereby, if the content of the situation strongly influences the access to concepts, the effect of negation could be due to the situational variable. To test whether the situational presence is critical to induce the negation effect, Kaup (2001) runs two experiments, with a careful manipulation of the linguistic materials, with a similar probe-recognition task. In the first experiment, the sentences described a situation where the verb involved the act of "creating" the object to which the noun referred ("*to bake a cake*"), while, in the second experiment the verbs involved the "destruction" of the referred object ("*to burn a paper*"). The results of the first experiment replicated those of MacDonald & Just (1989), showing lower reaction time for the negated concept compared to the affirmed one. More interesting, in the second experiment the negation effect was still found, although the size of the effect was considerably reduced compared to the "creation" sentences. The author proposed that the results observed for the "creation" sentences were indeed due to the presence/absence of the object in the situation, and the diminished effect of negation in the "destruction" sentences was compatible with the two-level theory. That is, two different variables operate at different level, generally speaking the negation operator works at a text base-level representation making the negated concept less accessible, whereas with destruction verbs the negation operator denote the non-absence of the concept, reducing the impact of negation effect, which suggest a situational level effect. In other words, the negation effect is strong when the negated concept is non-existent in the situation, but it became weaker when the negated concept remains present in the situation. The two-level theory was further corroborated by Kaup & Zwaan (2003), who additionally manipulated the temporal delay of the probe presentation in a similar probe-recognition task with texts containing colour word mentioned in a negative or an affirmative statement. The results showed that at an early temporal delay (500 ms), the negation effect on colour-concept accessibility meanly depend on the negation operator influence, whereas, at longer temporal delay (1500 ms), the accessibility to the colour-concept was affected exclusively by the situational content. This evidence supports the idea of a modal mental model with different steps of processing and rejects the amodal explanation that meaning can only be constructed from a propositional text base.

A unified theory that accounts for the "difficulty processing" model and for the "accessibility reduction" model, is the two-step simulation hypothesis (Kaup et al., 2006, 2007). This theory claims that to represent a negated meaning, the simulation of the affirmative counterpart is firstly activated, and only in a second step the actual state of affairs (negated situation) is processed and then simulated. Then, the slower response time and the lower accuracy associated with processing negated language reflect a higher resource cost derived from the additional simulation, required to fully understand negative sentences. The two-step simulation theory would also explain the reduction-accessibility effect of negation found by MacDonald & Just (1989), that is, the participants would be slower to answer to the negated probe relative to the affirmative probe, because they first simulated the actual situation described in the sentences, and in a second step they needed to update such simulation according to the presupposition negated sentences.

Although those studies offered an interesting view of the differences in understanding negative and affirmative language, they still left unknown which is the brain mechanism underlying such difference. A recent corpus of studies, attempted to answer the question of "how" negation works, focussing on action-related language. The main finding emerged from these researches is that the negation of an action verb seems to induce a "disembodiment" effect on motor system (de Vega et al., 2016; Papeo et al., 2016; Tettamanti et al., 2008), as the reduction of brain activity in motor-related areas suggests, by blocking the semantic access to the meaning of the negated action. In the next section we will discuss this body of investigations.

2.1 The *disembodiment* effect of negated action language on motor system

The first evidence of motor system activity during the process of action negation, comes from an fMRI study of Tettamanti et al. (2008). Participants were instructed to passively listen to action and abstract sentences presented either in affirmative (action: "*Now I push the button*"; abstract: "*Now I appreciate the loyalty*") or negative form (action: "*Now I do not push the button*"; abstract: "*Now I do not appreciate the loyalty*"), while the brain hemodynamic signal was recorded. The authors hypothesized that if negation comprehension blocked the representation of the negated concept, then reduced brain activity in the left fronto-parieto-temporal system should be observed for negated action compared to affirmed action, while negated abstract sentences, compared to affirmed abstract sentences, would induce a decrease in the posterior cingulate cortex activity. As shown in Figure 2.1A, the contrast in sentences polarity regardless their content, showed that affirmative sentences were associated with higher signal in the right middle frontal gyrus, in the right middle occipital gyrus and in the left palladium relative to negative sentences. The time course analysis (Figure 2.1D) pointed out that the reduced signal in negative sentences, compared to affirmative sentences, reflect deactivation of the aforementioned neural networks. The contrast between action and abstract language confirmed a lateralized activation of the left fronto-parieto-temporal circuit, corresponding to a selective activation of the motor system for action sentences (Tettamanti et al., 2005), whereas the increased signal in the left ventral inferior frontal gyrus, the left inferior and middle temporal gyri, and the posterior cingulate cortex was associated with affirmative abstract sentences (Figure 2.1B). More important, as showed in Figure 2.1C, the processing negated action sentences induced a significant reduction in the activity of the fronto-parieto-temporal network, whereas negated abstract sentences induced deactivation in the posterior cingulate cortex.

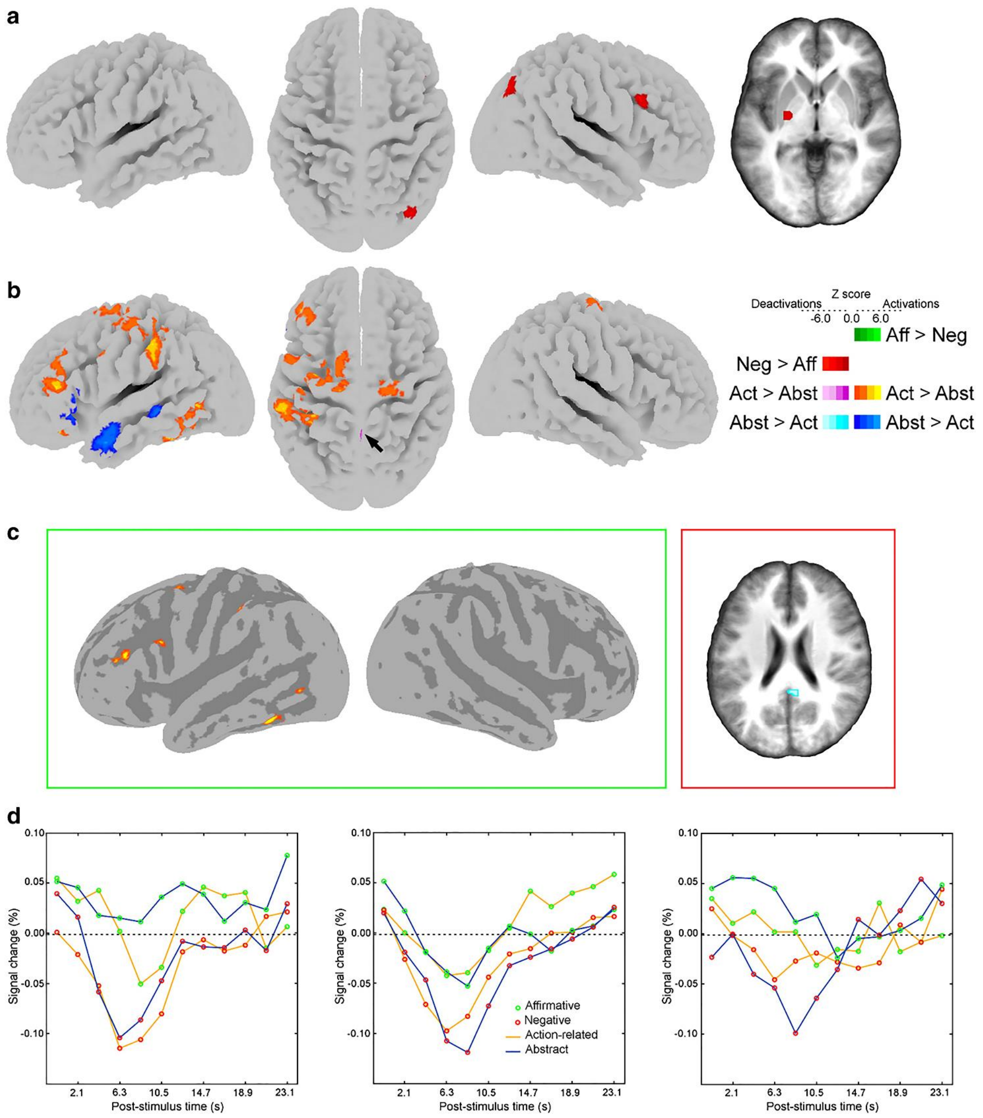

Figure 2.1. (Tettamanti et al., 2008). A) Deactivations elicited by negative sentences (Neg>Aff, red color scale). (B) Pattern of activation or deactivation for action-related (orange and magenta respectively) and activation for abstract sentences (blue colour). (C) As represented in the green frame, affirmative action-related sentences increased signal in the left fronto-parieto-temporal areas compared to the negated sentences, whereas the signal negative abstract sentences in contrast to their affirmative counterpart reduced the activation in the posterior cingulate cortex (red frame).

(D) Temporal dynamics of deactivations for negative sentences compared to affirmative sentences, independently of the context, in the right middle frontal gyrus (left), in the right middle occipital gyrus (middle) and in the left pallidum (right).

Similar results were later reported by Tomasino et al. (2010), who found that reading negative imperative action verbs ("*don't grasp*") reduced activity in both bilateral motor primary and premotor cortex compared to affirmative verbs ("*do grasp*"). Unlike Tettamanti et al. (2008) who did not record behavioural data, in this study participants performed a lexical decision task involving hand-action imperative verbs and pseudo-imperative verbs presented in both negative and affirmative form. Compatibly, reaction times were longer for negative verbs compared to the affirmative ones. Taken together, these results hint that the effect of negation could be explained by the mediation of an inhibitory mechanism, a proposal that we will unfold in the next section.

The reduced activation in motor areas found in neuroimaging studies, is also supported by behavioral evidence in which the semantic processing of negated action language reduced the peripheral motor activity (Aravena et al., 2012; Bartoli et al., 2013; Foroni & Semin, 2013; García-Marco et al., 2019). For example, Aravena et al. (2012) used a grip-force sensor to directly evaluate the effect and the temporal course of action-negated language processing on motor brain activity. Participants listened to sentences containing affirmative verbs, negative verbs and concrete nouns (control condition), while they hold the grip-force sensor with their right hand in a fine grip. The authors found a comparable grip-force during the first 200 ms of target-words presentation among the three conditions, and, from this time point only the processing of affirmative sentences staidly enhanced the grip force until the end of the sentences, while no change was observed during negation processing. The lack of increase grip-force for negative sentences has been interpreted by the authors as the consequence of sensory motor inhibition that block the access to the lexical-semantic information of the negated concept. On the same line, Bartoli et al. (2013) assumed that if sentential negation blocks the access to the embodied representation of the concept expressed in a linguistic content, then, the interference effect usually seen when language and motor execution are performed simultaneously (Boulenger et al., 2006), should be weaker. Indeed, listening negative, but no affirmative, action sentences describing proximal or distal motion weakened the interference with the corresponding kinematic parameters of congruent movements, confirming the idea of a disembodiment effect of negation. In addition, Foroni & Semin (2013), measured the zygomatic muscle activity on the left side of participant's face, while they read affirmative and negative action sentences referring to the target muscle ("*I am smiling*") or not ("*I am frowning*"). The analysis on electromyographic response showed that affirmative action-sentences involving the zygomatic muscle enhanced its activity, while their negative counterpart ("*I am not smiling*") induced the inhibition of the muscle.

The effect of action negated language on motor activation has also been found in some experiments measuring motor excitability. Liuzza et al. (2011), investigated for the first time the modulation of CSE during the comprehension of affirmative and negative action sentences, by means of TMS. Particularly, they used a novel TMS protocol that is named paired-pulse TMS (pp-TMS). While spTMS effect may occur at both cortical and spinal level, ppTMS allows a reliable measure of purely cortical activation. That is, with this paradigm the observed MEPs modulation takes place at cortical level, reflecting the activation of different populations of inhibitory and excitatory interneurons, without affecting spinal circuits (Di Lazzaro et al., 2008; Reis et al., 2008). The ppTMS consist of a conditioning stimulus (CS) below the rMT followed by a suprathreshold test stimulus (TS). The interval between the two stimuli (interstimulus intervals, ISIs) variated from 1-5 ms, inducing an inhibitory effect on cortical interneurons (short intracortical inhibition, SICI), indexed by reduction in MEPs amplitude. On the contrary, an ISI of 7-20 ms produced a facilitation on excitatory neurons (intracortical facilitation, ICF), resulting in MEPs increment (Kujirai et al., 1993; Ziemann et al., 1996). With that in mind, Liuzza et al. (2011), measured ICF from left M1 while participant read action-related and abstract sentences, presented in affirmative and negative form. The pp-TMS pulses were randomly delivered in an interval between 500 and 700 ms after the onset of the sentence. The analysis on MEPs amplitude show CSE reduction for processing action-related sentences relative to abstract sentences, confirming previous result (Buccino et al., 2005). Furthermore, action sentences polarity modulated ICF, expressed by the reduction of excitatory neuron activity for affirmative action sentences compared to their negative counterpart. The authors proposed that the lack of cortico-motor reduction for negative action language, reflects the suppression of the sensorimotor simulation induced by the negated action. In other words, sentential negation acts like a gate, inhibiting or blocking the access to the corticospinal sensorimotor simulation of the negated sentences representation. However, this study measured physiological modulation at a relative late interval (500-700 ms), while motor simulation of word's representation process seems to take place also at earlier latency (Olaf Hauk & Pulvermüller, 2004; Pulvermüller et al., 2001; Pulvermüller, Hauk, et al., 2005). In addition, it has been observed that the first stage of word semantic process occurs within 250 ms (Papeo et al., 2015). In that regard, and to further empirically test the two-step simulation theory, Papeo et al. (2016, Exp 1) used chronometric spTMS to evaluate the activation of action-hand motor portion (left precentral gyrus) at different time points (250, 400 and 550 ms) of action and abstract verb presentation, preceded by an affirmative (action: "*Now I write*"; abstract: "*Now I wonder*") or negative (action: "*I don't write*"; abstract: "*I don't wonder*") context word. The rationale was as follows; if at the initial stage (short intervals) affirmative and negative action verb equally modulate motor excitability, and at a later stage (large intervals) negation reduces motor excitability, then the two-step simulation theory would be confirmed. On the contrary, an early polarity-driven differential activation of left precentral gyrus, would indicate that negation is immediately integrated in the negated meaning construction. The results are in favour of this latter assumption. MEPs amplitude for affirmative action-verb was greater compared to affirmative abstract verb and, crucially, to their negative counterpart (Figure 2.2A). Moreover, the negation effect on motor simulation already takes place at initial step of the semantic verb processing (Figure 2.2B), opposing the idea of two-step simulation process.

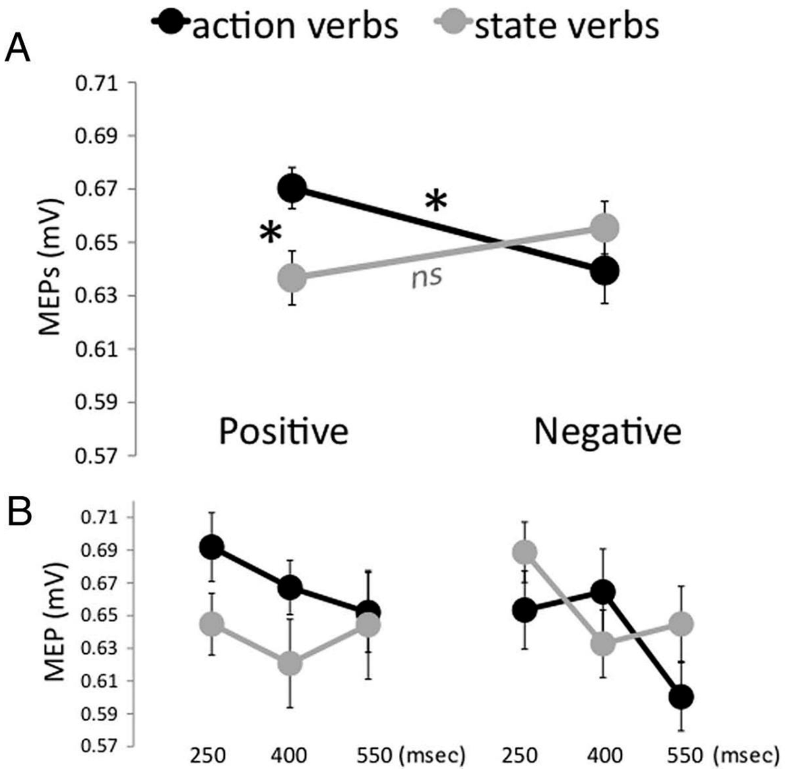

Figure 2.2. (Papeo et al., 2016). A) Mean MEPs amplitude of action and state verbs for both affirmative and negative form, averaged by time B) and divided for the three-time interval.

In sum, in this section, we presented different sources of evidence of the disembodiment effect of negation, as indicated by the reduction of motor network activity for negated action language. Still, the neural mechanism underlying the inhibited or blocked access to the negated concept is not clear. In the next section we will discuss a new recent hypothesis, proposing that understanding negated meaning involves the neural network of inhibitory response.

2.2 The Reusing Inhibition for Negation hypothesis

The RIN hypothesis (Beltrán et al., 2018; de Vega et al., 2016; Liu et al., 2020) posits that the neural mechanism of motor inhibition response is implicated in the processing of sentential negation. The authors suggest that since negation, as we largely reviewed above, blocks or reduces the accessibility to the previously activated representations and the inhibitory system can also operate to suppress a previously activated representation (Nakata et al., 2008), it is coherent to hypothesized that negation understanding reuses the inhibitory mechanism control. Next, we will briefly describe the neural basis of the inhibitory circuit and discuss evidence supporting the RIN hypothesis.

2.2.1 The neural network of response inhibition

The process of response inhibition is a cognitive mechanism critical to cancel an inappropriate action to prevent unwanted behaviours that can interfere with the desired goal. The most commonly employed behavioural paradigms to assess the ability to inhibit prevailing response are the Go-NoGo task (Donders, 1969; Drewe, 1975) and the stop-signal task (Logan, 1994; Logan et al., 1984; Verbruggen & Logan, 2009). Both paradigms consist of measuring performance in a two cue-based choice procedure; one of the cues instructs the participants to perform the motor response, whereas the other cue indicates the need to restrain themselves from responding. In the Go-NoGo task, participants have to inhibit the response in the NoGo trials and the number of commission errors they made in this condition is an index of inhibitory control failures. For the stop-signal task, all the trials initially involve a Go cue, but in some trials after a variable interval a Stop cue appears indicating that participants have to refrain from responding. The inhibitory control is indexed by the duration of the stopping process, that is the stop signal reaction time, in the trials were an inhibitory response is required (stop trials). Although the literature links response inhibition with the activation of several areas on frontal lobe, of the parietal cortex and of the insula (see Bari & Robbins, 2013 for a review and Zhang et al., 2017 for a meta-analysis), two brain region seem to be crucial in stopping motor action: the right inferior frontal gyrus (rIFG) (see Aron et al., 2014; Chambers et al., 2009 for reviews) and the pre-supplementary motor area (pre-SMA) (C. Y. Chen et al., 2009; Mostofsky & Simmonds, 2008; Obeso et al., 2017) (Figure 2.3).

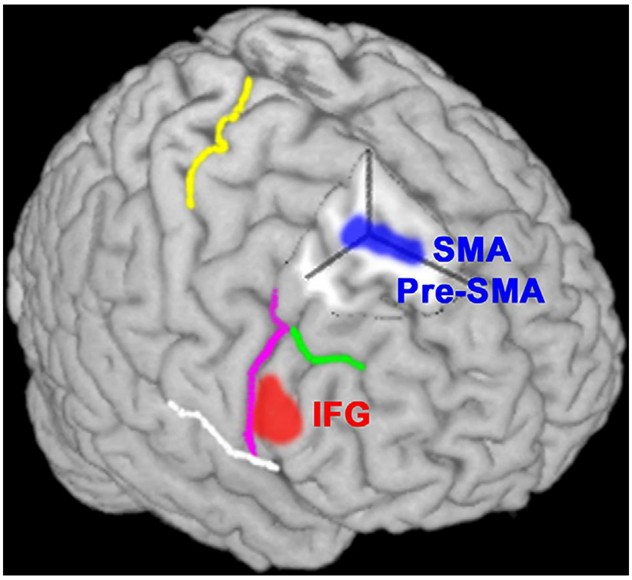

Figure 2.3. (Chambers et al., 2009). Cortical substrate of the human brain regions involved in the mechanism of inhibitory response.

The studies with brain patients provided substantial support that damage in the pars opercularis of rIFG (Aron et al., 2003) and in the pre-SMA (Floden & Stuss, 2006) induce significantly slower reaction time in a stop-signal task compared to the control group. In addition, the temporary disruption of rIFG brain activity, by means of low-frequency rTMS or continuous TBS, reduced the inhibitory performance in a stop-signal task executed with both hands (Chambers et al., 2006; Verbruggen et al., 2010), especially when the prepotent response highly compete with the response in a flanker task (Chambers et al., 2007), that measures the ability to suppress competitive response. On the other hand, offline inhibitory rTMS over pre-SMA impaired the inhibitory control in a stop signal task, leading to higher stop signal reaction time and to an increment in the error rates (C. Y. Chen et al., 2009). Nevertheless, continuous TBS over pre-SMA, but not over rIFG, improved the inhibition of motor response, as reflected by faster stop signal reaction time, compared to sham stimulation (Obeso et al., 2017). Although the results are counterintuitive (improvement in the stop-signal task after the inhibition of pre-SMA activity), the authors conclude that the pre-SMA plays a crucial role in motor inhibition, since the enhancement in the behavioral performance could reflect a compensatory effect of distant areas connected to the right pre-SMA across the left hemisphere network.

From these studies, a clearly critical involvement of both rIFG and pre-SMA emerges. Then, which one of the two areas is really necessary in the inhibitory mechanism of response? Since the two areas are functionally and structurally connected to each other (Aron et al., 2007; Swann et al., 2012) and since the activation of pre-SMA seems to occur before the IFG activation (Neubert et al., 2010; Swann et al., 2012), it is possible that pre-SMA is involved in pre-setting and/or triggering the IFG response (Aron, 2011).

With these premises, some authors (Aron, 2011; Aron et al., 2014; Chambers et al., 2009) proposed a model of the inhibitory mechanism based on the fronto-basal-ganglia network, mainly lateralized in the right hemisphere, which conceive the pars opercularis of the IFG as the crucial region. According to this model, the rIFG implements the inhibitory motor stopping to M1 by directly exciting the subthalamic nucleus, that activates the globus pallidus pars interna leading to a suppression of thalamus activity. This inhibition induces the suppression of the excitatory projections to the M1, and, consequently, hold back the motor programs generated by the thalamo-cortical connection, including the ones in the speech and hand system (Figure 2.4).

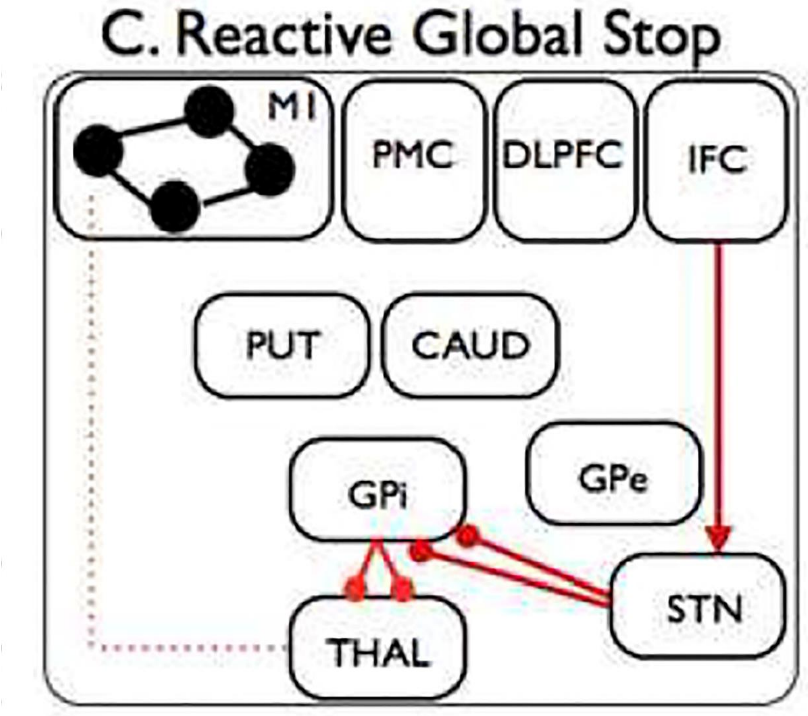

Figure 2.4. (Aron et al., 2011). The fronto-basal-ganglia model of inhibitory circuit for global stopping control.

Then, if the inhibitory circuit of motor response underlies the "disembodiment" effect of negation, it is likely to expect the activation of the rIFG, and/or the pre-SMA, during the processing of negated language.

2.2.2 The relationship between the inhibitory mechanism and the sentential negation processing

In spite of the recency of the RIN hypothesis of negation there is a growing evidence supporting the recruitment of the inhibitory system during negation understanding (Beltrán et al., 2018; de Vega et al., 2016; García-Marco et al., 2019; Liu et al., 2020; Papeo et al., 2016). For example, de Vega et al. (2016) measured the EEG signal, while participants performed a dual-task version of the Go-NoGo paradigm. Participants were presented with affirmative (*Now you will [yes] cut the bread*) and negative (*Now you will not cut the bread*) hand-action sentences, while a Go or NoGo cue appeared 300 ms after the verb presentation. Additional filler sentences (Afterwards you will [yes]/no call the taxi), which were not be included in the analysis, were introduced in the task with the aim of increasing the number of Go trials (70%), making more difficult the generation of an inhibitory response in the NoGo trials (30%). Since it is well known that NoGo trials enhance the amplitude of N1, N2 and P3 components (Bokura et al., 2001; Maguire et al., 2009; Smith et al., 2008) and increase the fronto-central theta (4-7 Hz) and delta (1-3 Hz) band power (M. X. Cohen, 2014; Harper et al., 2014; Huster et al., 2013; Nigbur et al., 2011) they can be considered robust indices of the inhibitory processes. Therefore, a selectively modulation on these neural measures by negative action sentences, would reflect that processing the negation recruits the inhibitory network. As the authors predicted, sentences polarity strongly modulated the theta band at an early interval (200-550 ms) of the cue onset, that is, in the NoGo trials, negative sentences reduced fronto-central theta power, compared to their affirmative counterparts. Such effect was explained as an inhibitory priming induced by the negation that reduced the neural inhibitory resources needed to suppress the response in NoGo trials, compared to affirmative NoGo trials. Further evidence supporting the RIN hypothesis, was reported by Beltrán et al. (2018), who used a stop-signal task with affirmative and negative hand-action sentences. The sentences were presented word by word, and participants were instructed to respond as quickly and accurately as possible to a Go cue appearing 700 ms after the onset of the verb, however, if they heard a tone (Stop signal) they have to restrain themselves, inhibiting the response. The results showed that when the response was successfully inhibited in stop trials induced larger N1 amplitude compared to the correct Go trials, for both affirmative and negative contexts, but the successful trials for negative sentences increased more N1 amplitude than for affirmative sentences

(Figure 2.5A). Additionally, the source localization of ERP analysis, identified the rIFG as the principal region of interest, which showed larger magnitude for negative sentences relative to their affirmative counterpart in the successful stop trials, and relative to negative sentences associated with unsuccessful stop trials (Figure 2.5B).

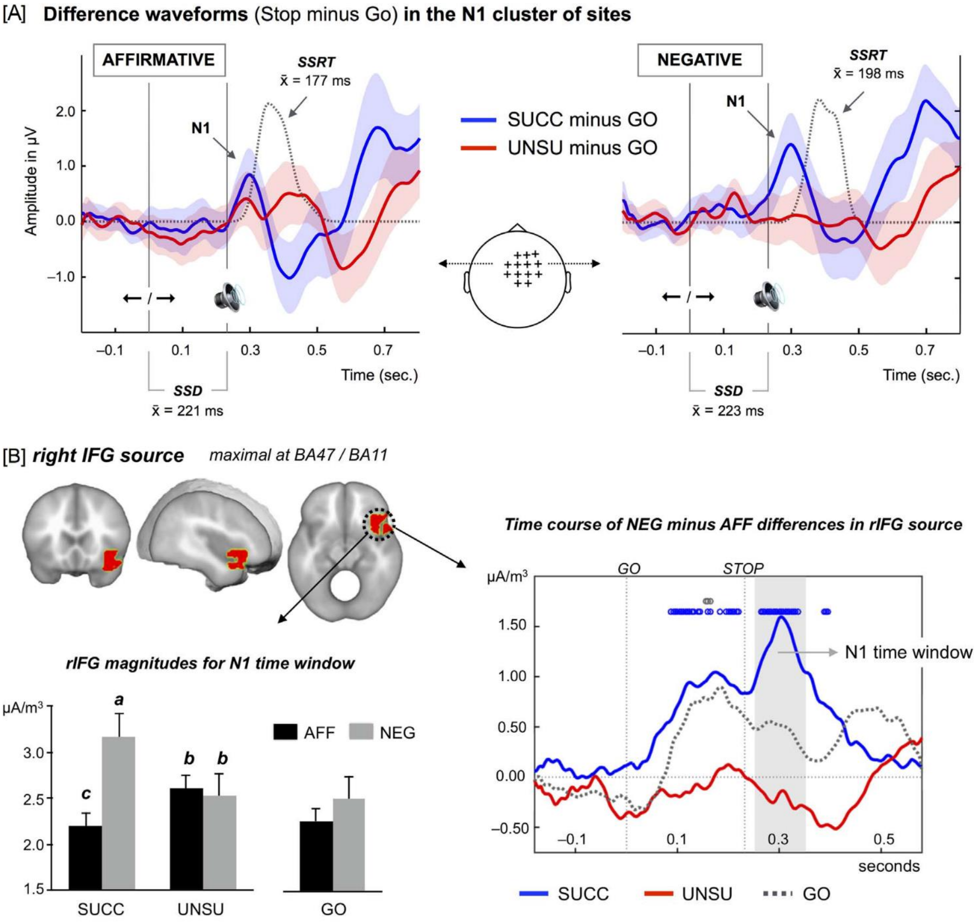

Figure 2.5. (Beltrán et al., 2018). A) N1 component modulation (Successful Stop – Go and Unsuccessful Stop – Go) for affirmative (left) and negative (right) sentences. B) Brain source localization in the rIFG of the N1 component (left-top). The mean current density values (bottom-left) indicated a statistical difference between affirmative and negative context in the successful trial, while no difference was shown for the unsuccessful trials. Temporal course of Negative-Affirmative contexts in the rIFG source for all the conditions (Go, Successful stop, Unsuccessful stop).

This pattern of neural activity was reinforced by the behavioral results, revealing slower stop-signal reaction time for negative than for the affirmative trials, suggesting that the former interfere with response inhibition. Overall, these findings extend those of de Vega et al. (2016), demonstrating that processing negation sentences required stronger inhibitory activity, as expressed by the increase of N1 amplitude, and that the source of such activation is located in the rIFG, one of the main regions of the inhibitory network (see the previous section).

Taken together, these studies confirm that negation modulates the inhibitory processes in a subsequent task as marked by the decrease of theta power and the increase of N1 amplitude, but they did not investigate the opposite relationship, that is, whether a pre-setting inhibitory state influence the comprehension of negated action sentences. Liu et al. (2020) aimed to investigate the bidirectional interaction between negation and inhibitory processes, combined a classical Go-NoGo task and a subsequent reading task with affirmative and negative action sentences. In each trial, the participants initially performed the Go-NoGo task, assuming that the NoGo condition activates an inhibitory state, and then was followed by an affirmative or a negative action sentences, to be carefully read. After revealing that the Go-NoGo task was working properly, as shown by the enhance of the N2 and P3 component for the No Go trial compared to the Go trials, the EEG analysis showed that, fallowing to a NoGo trial, the comprehension of action-negated sentences induced less positive ERP waveform compared to the affirmative sentences, while no effect emerged for the Go trials. Moreover, as seen before (Beltrán et al., 2018), the source analysis of this effect revealed an increase in the activity of two brain regions, rIFG and the left middle frontal gyrus, NoGo-negated sentences trials relative to NoGo-affirmative trials. This study provides the first evidence of a bidirectional influence between the negation process and the mechanism of the inhibitory response, reinforcing and extending the RIN hypothesis.

Together with EEG studies, the evidence supporting the RIN hypothesis comes from neurophysiological (Papeo et al., 2016) and behavioral (García-Marco et al., 2019) studies. As previously described, Papeo et al. (2016, Exp1) showed that spTMS over the M1, induced lower MEPs for the comprehension of negated action verbs compared to their affirmative counterpart, while no differences in CSE emerged for the state verbs. To further investigate the possible link between the inhibitory mechanism and the negation processing, in a second experiment involving the same material of the first experiment, they measured the cortical silent period (CSP), a proposed marker of intracortical inhibition, which consist of an interruption of the voluntary muscle contraction following a suprathreshold TMS pulse of the contralateral motor cortex. The CSP duration (Figure 2.6) is an index of intracortical inhibition due to the activation of Gamma-aminobutyric acid$_B$ (GABA$_B$) inhibitory interneurons that synapse on pyramidal neurons (R. Chen et al., 1999; Inghilleri et al., 1996; McDonnell et al., 2006), in fact it has been demonstrate a positive correlation between the duration of CSP and the activity of these neurons (Cantello et al., 1992; Inghilleri et al., 1993; Schütz-Bosbach et al., 2009).

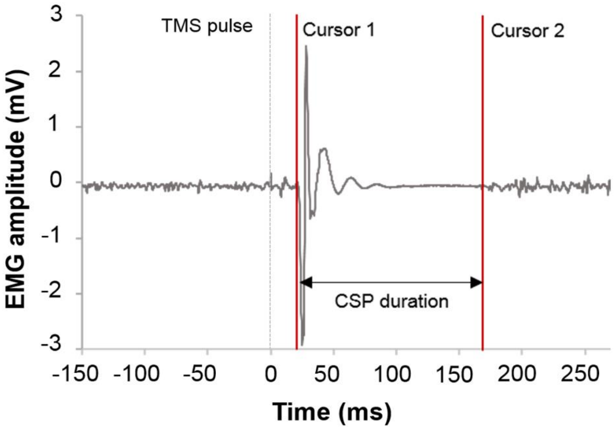

Figure 2.6. (Wilke et al., 2016). Representation of the CSP of a single trial after the MEP onset. The two cursor line (red) indicate the starting and the ending of the CSP.

The results revealed shorter CSP for the comprehension of affirmative action verbs than for the same verbs presented in a negative context, suggesting an enhancement in the intracortical inhibitory activity, supporting the RIN theory.

More recently, García-Marco et al. (2019) proved that sentential negation delayed the typing of the negated action-verb, due to the involvement of the mechanism specialized in response inhibition. The authors used sentences presented in a both affirmative and negative context, including manual action verbs (*There is the door. Today you are [not] going to **open** it*), non-manual action verbs (*There is the woman. Today you are [not] going to **talk** to her*) and non-action verbs (*Here is a lie. Now you will [not] believe it*). The primary sentences were presented one word a time, and when the target verb appeared, participants were instructed to type it as fast and accurately as possible. The analysis on whole-word lag measure, an index of the typing execution mechanism, showed a delay in the typing of negative manual action verbs, compared to their affirmative counterpart, to negative non-manual action verb and to negative non-action verbs. Therefore, the inhibitory effect of negation is effector-specific, and it affects the execution stage of typing process. Moreover, according to the literature discusses so far (Beltrán et al., 2018; de Vega et al., 2016; Liu et al., 2020; Papeo et al., 2016), the authors speculated that the delay observed in the writing of negated manual action verbs is caused by the direct recruitment of the inhibitory mechanism of response.

2.3 Conclusion

The studies discussed in section 2 provide strong initial empirical evidence in favour of the RIN hypothesis. However, as we mentioned a few times in this thesis, to directly assess the functional influence of the inhibitory circuit in the process of negated meaning, further study employing a “causal” methodology (e.g., rTMS) are needed.

PART 2:

EXPERIMENTS

Objectives and hypotheses of Experiment 1

Objective 1: Investigate the functional role of the motor system in the memory for action language, by modulating the activity of M1, via tDCS.

Hypothesis: Enhancing M1 activity will selectively improve the performance in the memory task for the action sentences

Objective 2: Monitoring whether the tDCS-induced physiological changes, predict the behavioral performance in the memory task.

Hypothesis: The increase in motor excitability due to active tDCS positively correlates with the improvement in memory performance for action language.

Chapter 3: Experiment 1

Enhancing Motor Brain Activity Improves Memory for Action Language: A tDCS Study

Publication:

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Chapter 3: Enhancing Motor Brain Activity Improves Memory for Action Language: A tDCS Study.

Abstract

The embodied cognition approach to linguistic meaning posits that action language understanding is grounded in sensory-motor systems. However, evidence that the human motor cortex is necessary for action language memory is meager. To address this issue, in two groups of healthy individuals we perturbed the left primary motor cortex (M1) by means of either anodal or cathodal transcranial direct current stimulation (tDCS), before participants had to memorize lists of manual action and attentional sentences. In each group, participants received sham and active tDCS in two separate sessions. Following anodal-tDCS (a-tDCS), participants improved the recall of action sentences compared to sham-tDCS. No similar effects were detected following cathodal-tDCS (c-tDCS). Both a-tDCS and c-tDCS induced variable changes in motor excitability, as measured by motor-evoked potentials (MEPs) induced by transcranial magnetic stimulation (TMS). Remarkably, across groups, action-specific memory improvements were positively predicted by changes in motor excitability. We provide evidence that excitatory modulation of the motor cortex selectively improves performance in a task requiring comprehension and memory of action sentences. These findings indicate that M1 is necessary for accurate processing of linguistic meanings, and thus provide causal evidence that high-order cognitive functions are grounded in the human motor system.

3.1 Introduction

According to the embodied cognition (EC) theories, understanding action language is associated with the activation of perceptual and motor processes which simulate the referred action. For instance, action words or sentences activate sensory-motor circuits required to produce the action being described (Barsalou et al., 2008; Fischer & Zwaan, 2008; García & Ibáñez, 2016; Glenberg et al., 2008). A conspicuous number of behavioral (de Vega et al., 2013; Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006), neuroimaging (Aziz-Zadeh et al., 2006; de Vega et al., 2014; Raposo et al., 2009; Tettamanti et al., 2005) and EEG studies (Moreno et al., 2013, 2015; van Elk et al., 2010) have provided evidence supporting the EC approach to language meaning. In particular, single-pulse transcranial magnetic stimulation (TMS) studies have shown that understanding action-related language modulates motor cortical excitability, as measured by motor-evoked potentials (MEPs) (Oliveri et al. 2004; Buccino et al. 2005; Papeo et al. 2009; Candidi et al. 2010; Scorolli et al. 2012). Taken together, these studies show a consistent involvement of the human motor cortex – i.e., a set of frontal brain areas involved in the control of body movements and including the primary motor cortex (M1) and premotor areas – during comprehension of action language and support the view that motor cortex activation reflects motor simulation of linguistic meanings.

It is worth noting that such conclusions are mainly supported by indirect correlational evidence that leaves unsolved the fundamental question of whether the motor cortex is causally essential for understanding action-related sentences or merely reflects such understanding – as contended by critics of EC theories (Leshinskaya & Caramazza, 2016; Mahon, 2015; Mahon & Caramazza, 2008; Papeo et al., 2013). For example, using a perturb-and-measure TMS protocol combining repetitive TMS and MEPs recording (Avenanti et al., 2007; Avenanti, Annella, et al., 2013), Papeo et al. (2015) showed that interference with the posterior middle temporal gyrus (pMTG), a key area involved in verb conceptual processing (e.g., Peelen et al., 2012), impoverished the semantic processing of verbs and disrupted MEPs modulation during comprehension of action language, thus suggesting that action simulation occurring in the motor cortex can reflect downstream processing of temporal areas. Remarkably, however, a few studies have also shown that TMS over M1 affects action language understanding. In their seminal study, Pulvermüller et al. (2005) used online single-pulse TMS over hand and leg representations in M1 to demonstrate a somatotopic-specific quickening of responses in a lexical decision task. On the other hand, Vukovic et al.(2017) administered online repetitive TMS (rTMS) to interfere with M1 activity and found delayed response to action words in a semantic task. Additionally, in two studies (Gerfo et al., 2008; Repetto et al., 2013) offline low-frequency rTMS over M1 delayed response to action-related words during morphological or semantic tasks. These behavioral effects of TMS provide causal evidence supporting EC theories. However, the neural mechanism underlying these effects remains unclear, as none of these studies monitored physiological changes induced by brain stimulation. Moreover, although increasing the excitability of frontal motor areas can lead to long-lasting behavioral gains (e.g. Avenanti et al., 2018; Fiori et al., 2018; Hashemirad et al., 2016) and, importantly, can enhance motor learning (for example, it ameliorated acquisition and retention of new motor skills or adaptation of previously learned ones; see Buch et al., 2017; López-Alonso et al., 2015; Nitsche, Schauenburg, et al., 2003; Reis & Fritsch, 2011), no prior study has tested whether enhancing M1 would also improve memory of action-related language.

The current study aims to fill these gaps, by investigating the potential facilitatory after-effects of M1 neuromodulation in an action-language memory task. To this end, we used transcranial direct current stimulation (tDCS) to test whether exogenous excitatory manipulation of M1 activity would improve memory performance of items associated with action verbs. Participants were tested in a delayed memory task inspired by recent behavioral studies (e.g., Dutriaux et al., 2018; Dutriaux & Gyselinck, 2016; de Vega et al. submitted). In these studies, participants' hand posture was manipulated to interfere with motor simulation while participants had to read and memorize linguistic material. In one of these studies, the authors presented lists of manipulable and non-manipulable objects and participants were instructed to memorize the items while adopting different hand postures. The authors found that during learning, keeping the hands behind the back rather than having them in front of onself selectively interfered with the recall of manipulable objects as compared to non-manipulable objects (Dutriaux & Gyselinck, 2016). In another study, the same research group (Dutriaux et al., 2018) tested whether postural interference could also be observed in the context of action-related language. In a learning phase, participants were exposed to object-verb sentences while keeping their hands back or in front. Researchers found that the hands back posture interferred with recall of object nouns (e.g., cup) exclusively when nouns appeared in the context of action verbs (e.g., to take a cup) rather than in the context of attentional verbs (e.g., to see a cup), suggesting that motor simulation has a functional role in language processing. These behavioral findings were replicated in a further electrophysiological (EEG) study that used a similar posture manipulation task (de Vega et al. submitted). Additionally, this EEG study revealed a fronto-central beta rhythm desynchronization (index of motor process) while participants read manual action sentences in the hands front posture, but this modulation was suppressed in the hands back posture, suggesting that the latter interferes with motor simulation in the motor cortex.

In the current study, like in the aforementioned studies (i.e., Dutriaux et al. 2018; de Vega et al. submitted), we tested performance on a delayed memory test: participants were initially presented with a set of sentences composed of object nouns presented in the context of either action or attentional verbs (learning phase); then, in the testing phase, we evaluated participants' ability to recall object nouns that were associated with action or attentional verbs, using a cued recall procedure. However, rather than testing the interferential effects of hand posture, we exogenously enhanced the motor cortex with tDCS and asked whether this manipulation improved memory performance with action sentences rather than with attention sentences. We targeted M1 using a classical bicephalic montage with a reference electrode over the supraorbital area, as modeling and neuroimaging studies indicate that this is best suited to modulate frontal motor areas (Datta et al., 2009; Ho et al., 2016; Jang et al., 2009; Opitz et al., 2015; Polanía, Nitsche, et al., 2011; Polanía, Paulus, et al., 2011; Stagg et al., 2009). We administered two different types of tDCS protocols over M1. In the experimental group, we administered anodal tDCS (a-tDCS), as classical studies have shown that anodal currents can enhance motor excitability (Nitsche, Nitsche, et al., 2003; Nitsche & Paulus, 2000, 2001; Stagg et al., 2018; Stagg & Nitsche, 2011) and such increase can be associated with behavioral gains (e.g. Alix-Fages et al., 2019; Convento et al., 2014; Hashemirad et al., 2016; Orban de Xivry & Shadmehr, 2014). We stimulated M1 for 20 minutes using 2 mA a-tDCS, as this protocol consistently increases motor excitability for up to 60 minutes (Batsikadze et al., 2013; Jamil et al., 2017). In different sessions, participants were tested following active a-tDCS and sham tDCS, which served as a baseline control session. We reasoned that if motor simulations occurring in the motor cortex while learning action sentences are functionally relevant, enhancing M1 activity through a-tDCS would selectively improve memory retrieval for action sentences in the a-tDCS relative to the sham session, providing new evidence of a functional link between the motor system and 'higher-order' cognitive functions such as comprehension and memory.

Additionally, to test polarity-dependent effects of tDCS, in a further group of participants we administered 2 mA cathodal tDCS (c-tDCS). While we expected that 2 mA a-tDCS would increase motor excitability and improve memory performance for action language, we had no similar expectation for the contrast group submitted to 2 mA c-tDCS. Although classical studies suggest cathodal currents over M1 tend to inhibit the excitability of the motor cortex, it is now established that tDCS effects are not linear and vary across individuals; in particular, c-tDCS at an intensity of 2 mA has been associated with an inconsistent pattern of results in different studies (e.g., Batsikadze et al. 2013; Wiethoff et al. 2014; Jamil et al. 2017). Yet, we selected this c-tDCS protocol to provide an adequate contrast to the anodal stimulation and rule out unspecific effects of brain stimulation. Therefore, we expected to find a facilitation following a-tDCS, with larger MEPs after a-tDCS relative to pre-stimulation level and MEPs following c-tDCS. We expected that c-tDCS should induce variable results among the participants, with approximately half showing trends for increased motor excitability and half showing trends for decreased motor excitability (Wiethoff et al., 2014), resulting in statistically null physiological and behavioral effects at the group level.

To monitor the physiological effect of a-tDCS and c-tDCS, MEPs to single-pulse TMS over the left M1 were recorded in each session before and after tDCS administration, allowing us to evaluate the inter-individual variability previously reported (Ammann et al., 2017; Chew et al., 2015; Kaup & Zwaan, 2003; López-Alonso et al., 2014; Strube et al., 2015; Wiethoff et al., 2014) and, most importantly, to test whether physiological changes in motor excitability following tDCS predict behavioral changes in memory performance. We hypothesized that improved performance occurring after a-tDCS would be associated with an increment of motor excitability. However, because c-tDCS is expected to induce variable physiological effects, we also tested whether increased motor excitability (irrespective of whether this was achieved via a-tDCS or c-tDCS) predicted larger action-specific behavioral improvements.

In sum, this neuromodulation study has several novelties in the field of embodied semantics: 1) it used for the first time a long-term dependent measure, rather than online neurophysiological measures, like MEPs, or online behavioral measures, like reaction times or reading times. This is relevant, because purely online effects reported elsewhere are compatible with a momentary neural resonance without further cognitive consequences, whereas a modulation of a delayed memory task indicates that the embodied representations have functional impact beyond the language encoding moment; 2) it provided a robust baseline condition, as the same participants performed the task in two sessions, after active tDCS and after sham tDCS, rather than using a less reliable between-participants contrast with a sham group; 3) it tested in the same participants how neuromodulation induced changes both in M1 corticospinal excitability and in the recall of action language and explored the association between both measures, suggesting a functional link between motor physiology and memory performance.

3.2 Material and methods

3.2.1 Participants

Fifty healthy undergraduate students participated in this study. The sample size was determined through a power analysis conducted using G*Power 3 software (Faul et al., 2007), with power ($1 - \beta$) = .95 and $\alpha = .05$. We expected a low-medium effect size ($f = .15$) and high correlation between measures ($r > .6$; de Vega et al. submitted). The analysis yielded required sample sizes of 25 participants per group. We thus decided to test 50 participants who were randomly assigned to two stimulation groups: 25 participants (6 men, mean age ± SD: 20.3 years ± 3.3) were assigned to the a-tDCS group and 25 participants (1 man, mean age ± SD: 19.6 years ± 1.3) were assigned to the c-tDCS group. All participants were right-handed, had Spanish as their mother tongue, and did not report any neurological disease, visual problems, or medicine intake. All students gave informed consent and received course credit for volunteering. The Research Ethics Committee of the University of La Laguna approved this study and the experiment was conducted according to the principles expressed in the Declaration of Helsinki.

3.2.2 Linguistic material

Two sets of 120 Spanish sentences with the format "verb + article + noun" were used. A total of 30 manual action verbs, 30 attentional verbs (Supplementary Table S1), and 120 nouns referring to manipulable objects were used to construct the sets. Within each set of sentences, each verb appeared twice associated with two different objects. The objects were not repeated within each set; however, the sentences in the two sets differed in the combination of nouns and verbs in such a way that if a given noun appeared with a manual verb in set 1 (e.g., *colgar un bastón* / to hang a cane), it was associated with an attentional verb in set 2 (e.g., *observar un bastón* / to observe a cane) and vice versa (Supplementary Table S2). Values of frequency and length of each verb were downloaded from the EsPal database, a web-accessible repository containing a comprehensive set of properties of Spanish words (Duchon et al., 2013). Manual and attentional verbs did not differ in frequency (mean ± SD: manual action = 23.83 ± 54.91; attentional = 56.84 ± 93.87; $t_{58} = -1.66$, $p = .10$) or length (manual action = 6.67 ± 1.37; attentional = 7.27 ± 1.87; $t_{58} = -1.41$, $p = .16$). In an additional normative study, 30 university students, who did not participate in the subsequent experiment, were asked to judge on a 7-point Likert scale the familiarity and concreteness of the verbs. The familiarity was similar for the two types of verbs (manual action = 6.24 ± .52; attentional = 5.97 ± .76; $t_{58} = 1.55$, $p = .13$), while, as expected, the manual action verbs were judged as more concrete than the attentional verbs (manual action = 5.72 ± .51; attentional = 4.28 ± .63; $t_{58} = 9.77$, $p < .001$), reflecting the intended semantic differences between the two types of verbs. The noun frequency and length values were 29.70 ± 195.20 and 6.35 ± 1.73, respectively. To assess whether the manual action sentences and the attentional sentences were semantically comparable, we utilized the search engine "Google" to check the number of co-occurrences of the verb-object pair for each sentences, by using quotation marks (Griffiths et al., 2007; Page et al., 1999; Sha, 2010). For both sets, the co-occurrence values of the manual action sentences did not differ from the values of the attentional sentences (set 1: manual action = 31,762 ± 55,992, attentional = 78,917 ± 343,442; $t_{118} = -1.05$, $p = .30$; set 2: manual action = 88,682 ± 310,006, attentional = 115,036 ± 409,065; $t_{118} = -.40$, $p = .69$).

3.2.3 tDCS

The tDCS was delivered by a battery-driven constant direct current stimulator (NeuroConn DC-STIMULATOR) and applied through a pair of saline-soaked surface sponge electrodes. The motor cortex electrode (5 x 7 cm) was fixed over the area representing the right first dorsal interosseous (FDI) muscle as identified by means of the TMS protocol described later, and the reference electrode (7 x 10 cm) was placed over the contralateral orbit, above the right eyebrow. In the active stimulation, the current was ramped up for 20 sec, followed by 20 min of 2mA, then ramped down for 20 sec. Participants were blind to the specific tDCS manipulation. For the sham stimulation, the electrode montage was the same and the electrodes were also attached for 20 minutes; however, the stimulation lasted for 30 sec (fade in/out 20 sec). This procedure ensures that the participants experienced the sensations initially associated with the onset of stimulation (mild local tingling), without inducing any effective modulation of cortical excitability. Also, this procedure ensured successful blinding of participants in previous research (Ambrus et al., 2012; Gandiga et al., 2006; Làdavas et al., 2015; Loo et al., 2010, 2012; Paracampo et al., 2018 but see O'Connell et al., 2012).

As mentioned above (see Introduction), while these parameters for a-tDCS elicit a facilitation on motor excitability lasting for more than 60 minutes (Batsikadze et al., 2013; Jamil et al., 2017), c-tDCS at 2 mA for 20 minutes can produce more inconstant after-effects (Batsikadze et al., 2013; Jamil et al., 2017; Wiethoff et al., 2014). To monitor tDCS current-induced after-affects, we assessed M1 corticospinal excitability using TMS.

3.2.4 TMS and electromyography (EMG) recording

To detect current-driven changes of motor excitability, we recorded MEPs by stimulating the hand representation in the left M1 with single-pulse TMS. MEPs were induced using a Magstim 200 magnetic stimulator (Magstim, Whiteland, Dyfed, UK) and a figure-of-eight magnetic coil (70 mm outer diameter; peak magnetic field 2.2 Tesla). The coil was held tangentially to the skull, with the handle pointing backward and laterally at 45° from the midline, resulting in a posterior–anterior direction of current flow in the brain. Surface EMG was recorded from the right FDI with Ag-AgCl electrodes in a belly-tendon montage with ground electrode on the wrist, using Topas (Schwarzer) electromyography system. The signals were amplified and filtered with a time constant of 10 ms and a low-pass filter of 2.5 kHz. The motor area for the right hand was defined as the point where stimulation consistently evoked the largest MEPs in the right FDI. To record MEPs, TMS intensity was set at 120% of the resting motor threshold (rMT), which was defined as the lowest intensity of output that evoked five small responses (~50μV) in the relaxed FDI muscle in a series of 10 stimuli (Rossini et al., 2015). The motor threshold means for participants of the anodal and cathodal groups were 37.0% ± 5.4 and 40.1% ± 5.6 of the maximum stimulator output. Participants were instructed to maintain their right hand relaxed and the absence of involuntary contractions was continuously verified throughout the entire experiment.

3.2.5 Procedure

The study involved a 2 Stimulation group (a-tDCS, c-tDCS) x 2 Sessions (active, sham) x 2 Type of sentences (action, attentional) experimental design. The Stimulation group was a between-participants factor, whereas the Session and the Type of sentences were manipulated within-participants.

Participants were randomly assigned to the a-tDCS or c-tDCS group. All participants were tested in two separate sessions. In the active session, they performed the memory task immediately after 20 minutes of active tDCS over M1; in the sham session, they performed the task following sham stimulation. The order of the sessions was counterbalanced across participants, and the two sessions were separated by at least three days.

To explore whether the behavioral results were associated with changes in motor excitability due to tDCS, MEPs induced by single-pulse TMS were recorded in three moments during the experimental sessions. First, a set of 25 baseline MEPs were collected before the active or sham tDCS was applied (Baseline); second, immediately after tDCS and before the memory task (T0), another set of 25 MEPs were taken; finally, after performing the memory task (lasting about 25 minutes) a final set of MEPs was collected (T25). (Figure 3.1A).

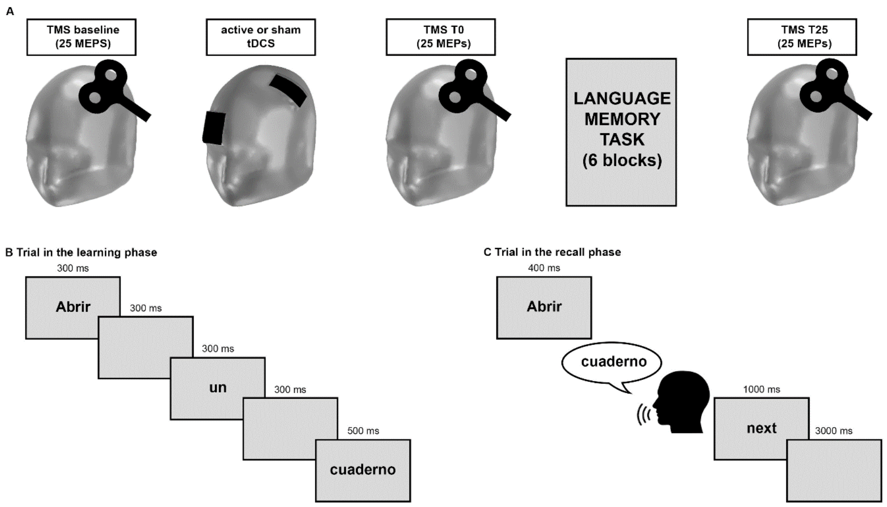

Figure 3.1. Structure of experimental procedure. (A) Schematic representation of behavioral and neurophysiological sessions. (B) Example of a trial in the learning phase (translation: to open/a/notebook). (C) Example of a trial in the recall phase.

The memory task included 12 experimental blocks, split into six blocks for each session. Each block was characterized by a learning phase, followed by a 45-second distractive task and a cue recall phase. The learning phase started with a filler sentence added at the beginning of each block to avoid the recall primacy effect, then five manual action and five attentional sentences were presented in a random order, and the participants were asked to memorize them and informed that they would receive a posterior memory test. The sentences were presented word-by-word (see Figure 3.1B), with a short inter-trial interval (2 sec), to minimize mental repetition of the sentence just read. Following the learning phase, a 45-sec distractive task was introduced to avoid the recency effect of memory, consisting of several trials, in which a target lower-case letter was presented beside a group of nine upper-case letters and the participants had to identify whether the target letter appeared in the group of the upper-case letters. Finally, in the recall phase, the verbs contained in the previous sentences were visually presented, and the participants had to recall orally the object associated with the verb (see Figure 3.1C). The answers were recorded and subsequently analyzed.

3.2.6 Data analysis

Three-way mixed factors ANOVAs by participants, with Group (a-tDCS and c-tDCS) as between-participants factor and Session (active and sham) and Type of sentences (action and attentional) as within-participants factors, were performed for memory accuracy, calculated as the percentage of words correctly recalled. The post-hoc comparison was performed using the Newman Keuls test. Partial eta^2 (η_p^2) was computed as a measure of effect size for the main effects and interactions, whereas repeated measures *Cohen's d* was computed for post-hoc comparisons (J. Cohen, 1992).

To corroborate the effectiveness of our manipulation, we further conducted an item analysis. Item accuracy was computed as the percentage of participants who correctly remembered each item. Since the data were not normally distributed (as shown by the Lilliefors test), they were analyzed with non-parametric Friedman ANOVAs. Two ANOVAs were carried out separately for the two Type of sentences (action and attentional), with Condition (a-tDCS-active, a-tDCS-sham, c-tDCS-active, c-tDCS-sham) as within-item factors. Post-hoc comparisons within factors were conducted with the Bonferroni-corrected Wilcoxon matched pairs.

MEPs were measured in mV and computed as the median of peak-to-peak amplitude for the three 25-MEPs sets obtained before and after tDCS for each session. MEPs contaminated by magnetic artefacts or preceding EMG activations were excluded from analysis (2%). For each session and group, we normalized the MEPs recorded after tDCS, averaging them at T0 and T25, resulting in values representing either increased (>1.0) or decreased (<1.0) motor excitability induced by tDCS. The normalized MEPs were entered into a two-way mixed factors ANOVA with Group (a-tDCS, c-tDCS) as between-subjects factor and Session (active, sham) as within-subjects factor.

To directly test whether the effect of tDCS on behavioral performance was predicted by tDCS-induced physiological changes, regression analyses were performed. To this end, an index of change in motor excitability was computed as the difference between normalized MEPs in the active vs. sham tDCS session and this index was entered as a continuous predictor in the regression model. In a similar way, an index of action-specific change in recall accuracy was entered as a dependent variable in the model. The index was calculated as follows. To assess action specificity, we subtracted accuracy values in the attentional sentences (serving as control condition) from accuracy values in the action sentences (experimental condition) separately for each session. Then, to assess the effect of tDCS, the two contrasts were combined in a differential index of the active vs. sham tDCS sessions. In a further regression model, we additionally entered the categorical predictor Group, to test whether similar relationships between physiological and behavioral data were observed in the two groups. To calculate Cohen's effect size (f^2) of regression we used the formula $f^2 = R^2/(1 - R^2)$, (J. Cohen, 1992).

3.3 Results

3.3.1 Behavioral results

The Group x Session x Type of sentences ANOVA performed on memory accuracy indicated a strong main effect of the Type of sentences ($F_{1,48} = 40.56$, $p < .001$, $\eta_p^2 = .458$). Manual action sentences were better remembered (mean accuracy ± SD: 35% ± 17) relative to attentional sentences (28% ± 16). More importantly, the expected triple Group x Session x Type of sentences interaction was also significant ($F_{1,48} = 5.03$, $p = .03$, $\eta_p^2 = .095$; Table 3.1).

To further explore such interaction, we performed separate Session x Type of sentences ANOVAs in the a-tDCS and c-tDCS groups, separately. The ANOVA performed in the a-tDCS group maintained the significant main effect of Type of sentences ($F_{1,24} = 12.52$, $p < .001$, $\eta_p^2 = .34$), indicating an advantage of manual action sentences (mean accuracy ± SD: 33% ± 16) relative to attentional sentences (27% ± 14, $p < .001$). Most importantly, the interaction Session x Type of sentences was also significant ($F_{1,24} = 4.34$, $p = .048$, $\eta_p^2 = .15$). Such interaction indicates that active a-tDCS improved memory for action sentences (35% ± 18) relative to sham a-tDCS (31% ± 16; $p = .048$, *Cohen's d* = .23), while no difference was found between sham and active a-tDCS for the attentional sentences (sham: 28% ± 14; active: 26% ± 17; $p = .40$).

The ANOVA conducted on the c-tDCS group also revealed a significant main effect of Type of sentences ($F_{1,24} = 29.94$, $p < .001$, $\eta_p^2 = 0.56$; action sentences: 38% ± 15 vs. attentional sentences: 29% ± 15), whereas neither the session nor the interaction produced significant effects (all $p > 0.30$), confirming that only active a-tDCS of M1 improved memory performance and that this was selective for action sentences (Figure 3.2).

	a-tDCS group		c-tDCS group	
	Sham	Active	Sham	Active
Action Sentences	31% ± 16	35% ± 18	38% ± 14	38% ± 18
Attentional Sentences	28% ± 14	26% ± 17	28% ± 15	30% ± 19

Table 3.1. Percentage of object recall for each session of the a-tDCS and c-tDCS groups (mean ± SD)

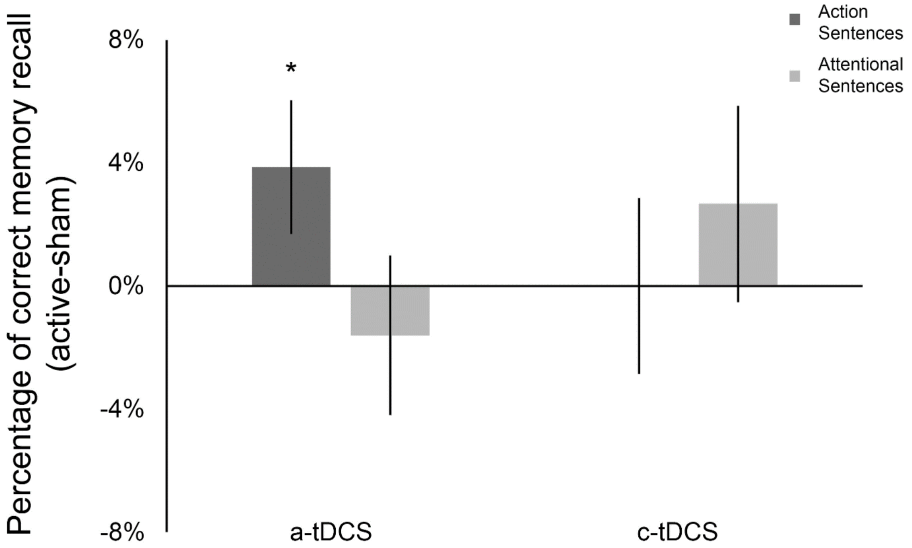

Figure 3.2. Differential means percentage of recalled items between active and sham sessions, as a function of stimulation group and type of sentences. Error bars indicate standard error of the mean (SEM). *P < 0.05

The item analysis carried out with Friedman ANOVA on action sentences was significant (χ^2 = 9.16, *p* = .03). The Bonferroni-corrected Wilcoxon tests performed in the a-tDCS group showed that the action sentence items were better remembered in the active session compared to the sham session (9% ± 6 vs. 8% ± 6; *p* = .05), whereas the same comparison was not significant in the c-tDCS Group (10% ± 6 vs. 9% ± 6; *p* = .40), confirming the result revealed by the main ANOVA by participants on memory accuracy. As expected, the Friedman ANOVA by items with attentional sentences was not significant (χ^2 = 3.67, *p* = .30).

3.3.2 MEP results

The Group x Session ANOVA on normalized MEPs did not reach statistical significance (all *F* < 2.14, all *p* > .15; Figure 3.3A). Yet, we directly tested the prediction that a-tDCS would increase motor excitability by using a one-sample t-test against 1. We found that normalized MEPs following active a-tDCS were marginally greater than 1 (t_{24} = 1.46, *p* = .078), suggesting a weak increase in motor excitability induced by a-tDCS (mean MEP amplitude ± SD: 1.10 ± 0.36). Indeed, the effect of a-tDCS was variable across participants (Figure 3.3B), with 18 showing increased MEP amplitudes and 7 showing decreased MEP amplitudes. On the other hand, one-sample t-tests showed a non-significant reduction in MEP amplitudes following c-tDCS (0.95 ± 0.15; *p* = .32): the effects of c-tDCS were quite variable across participants (Figure 3.3C) with 13 of them showing reduced MEPs and 12 showing increased MEPs. A planed comparison showed that MEPs following a-tDCS were larger than MEPs following c-tDCS (*p* = .04). No consistent modulations were observed following sham tDCS in either group (~1.00, all *p* > .95).

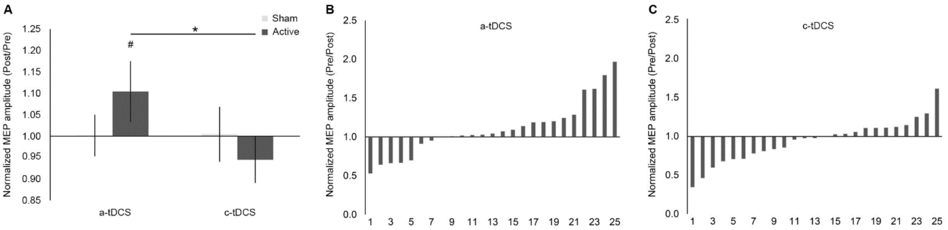

Figure 3.3. Changes in MEPs following tDCS. (A) Effect of Group and Session on normalized MEP amplitudes. MEPs following active a-tDCS tended to marginally increase relative to baseline levels. Error bars indicate SEM. * P < <0.05, $^{\#}$P = 0.078. (B) Individual normalized MEP amplitude values following active a-tDCS. (C) Individual normalized MEP amplitude values following active c-tDCS.

In a further analysis we tested whether individual variations in motor excitability induced by tDCS predicted changes in performance across the two groups. To this end, we first entered the memory accuracy index as a dependent variable and the normalized MEP index (normalized MEPs following active tDCS minus normalized MEPs following sham tDCS) as a continuous predictor in a regression model. The model was significant (R^2 = .08, $F_{1,48}$ = 4.43, *p* = .04; f^2 = .09) and it improved after the removal of two outliers with standard residual greater than 2 SD (R^2 = .11, $F_{1,46}$ = 5.84, *p* = .02; f^2 = .13; Figure 3.4). Interestingly, the model showed a positive relationship (β = .34, *p* = .02), indicating that larger normalized MEP index values (i.e., larger increase in motor excitability induced by tDCS) predicted increased memory performance with action language across the two groups.

Then, we asked whether the highlighted relationship was different in the two groups. We therefore entered Group as a further (categorical) predictor in the previous model and tested for any possible interaction between the two predictors. The whole model was significant (R^2 = .21, $F_{3,44}$ = 4.00, *p* = .01; f^2 = .27; Figure 3.4) and showed that the best predictor of memory performance was the predictor Group (β = .30, *p* = .032; Figure 3.4B), thus confirming the results of the main ANOVA, with larger action-specific improvements in the a-tDCS as compared to the c-tDCS group. Remarkably, the model also showed the significance of the predictor normalized MEP index (β = .28, *p* = .047; Figure 3.4A), but no interaction between the two predictors (β = .10, *p* = .44), indicating that similar positive relationships between changes in M1 excitability and action-specific memory improvements were observed in the experimental and control groups, although only the former showed consistent improvements at the group level.

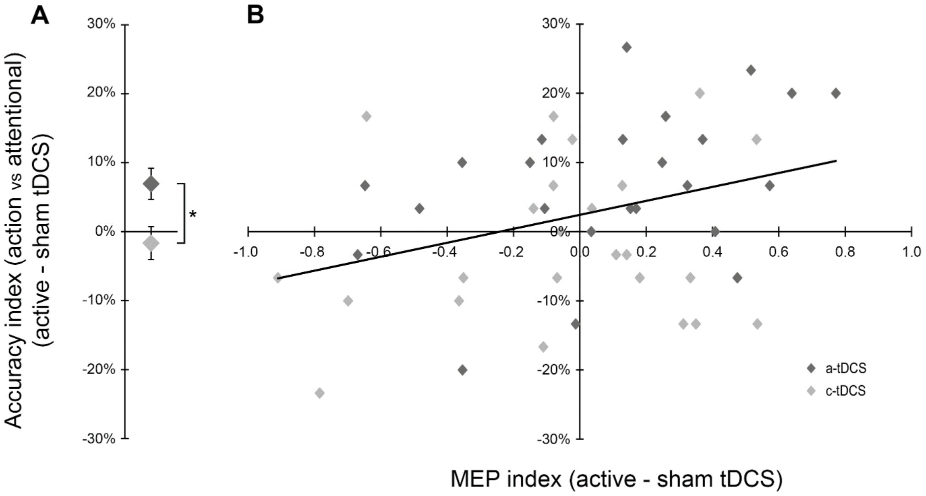

Figure 3.4. Result of the regression model. (A) Effect of the predictor Group. (B) Scatter plot of the relationship between normalized MEPs index and the differential accuracy index across groups.

3.4 Discussion

The present study investigated the functional role of the motor system in memory for action-related sentences. In two different groups we applied offline a-tDCS or c-tDCS over the participants' left M1 before they performed a language memory task, which consisted of memorizing sentences with manual action and attentional verbs. Compared to sham stimulation, a-tDCS improved the recall of sentences with manual action verbs but did not affect the recall of attentional sentences. No similar effects were observed following c-tDCS. As expected, a-tDCS tended to increase the amplitude of MEPs, although this effect was weak and only marginally significant. On the other hand, c-tDCS induced highly variable physiological effects, but no net change in motor excitability. Although only a-tDCS significantly improved action language performance at the group level, in both groups, participants who showed larger increase in motor excitability following active tDCS tended to show larger action-specific memory improvements, as shown by a regression analysis. These findings highlight a clear relationship between changes in the excitability of the motor cortex and action-specific memory performance.

The present study provides strong evidence of a causal link between the motor system and memory for action language. It demonstrates for the first time that an excitatory modulation of the motor cortex improves performance in the comprehension and later recall of action language. Previous research has shown that a-tDCS over M1 can transiently enhance a variety of motor functions including control of manual dexterity, endurance and maximal force production (Alix-Fages et al., 2019; Orban de Xivry & Shadmehr, 2014). Remarkably, a-tDCS improved learning of a variety of motor tasks (Buch et al., 2017) and, in particular, it improved performance in a serial reaction time task, which offers a well-established measure of implicit motor learning (López-Alonso et al., 2015; Nitsche, Schauenburg, et al., 2003; see Reis & Fritsch, 2011 for a review). Additionally, in a recent study, Buchwald et al. (2019) reported preliminary evidence that a-tDCS also improves motor learning in the speech domain. In the present research, however, we observed facilitatory effects of neuromodulation in an entirely different cognitive domain tapping on the processing of linguistic meaning. In spite of that, the mechanism underlying these effects could be similar, that is, a-tDCS applied on M1 improves motor learning and selectively enhances memory of action-related sentences, possibly because the motor cortex is causally engaged during both motor learning and action language comprehension and memory.

Importantly, our study complements and extends some recent TMS studies that have supported a functional relevance of the motor system in language comprehension. These studies have mainly reported delayed response to action language following online rTMS interference (Vukovic et al., 2017) or offline rTMS protocols that are supposed to inhibit motor excitability (Gerfo et al., 2008; Kuipers et al., 2013; Repetto et al., 2013). However, some obvious differences between our study and prior work must be noted. First, we investigated performance on a task requiring understanding and memorizing short noun-verb sentences, whereas previous studies used tasks requiring (online) morphological, lexical or semantic operations in response to action words. Second, here performance was improved by excitatory tDCS neuromodulations, rather than reduced by interferential or supposedly inhibitory TMS. Critically, rather than assuming a net physiological effect of brain stimulation, we directly monitored tDCS-induced changes in the excitability of the motor cortex and explored their relationship with changes in performance. Our study expands previous work by showing, for the first time, a linear relationship between tDCS-induced action-specific memory improvements and changes in motor excitability.

To what extent does this study contribute to clarifying the current debate on embodied-disembodied meaning (e.g., de Vega et al. 2008)? The ‘disembodied’ theories of linguistic meaning accept the overwhelming evidence that sensory-motor brain networks are activated during the comprehension of action language, but they doubt that these activations reflect a necessary aspect of meaning or play any functional role (e.g., Mahon and Caramazza 2008; Chatterjee 2010; Papeo et al. 2013; Mahon 2015). For instance, Mahon and Caramazza (2008) consider that the observed embodied effects are due to "cascade" spreading activation between the conceptual system to the sensory and motor systems, but that ultimately the proper representation of meaning is amodal or disembodied. Moreover, they claim that most evidence of embodied meaning comes from correlational measures, such as the BOLD signal activity, and corresponds to short-lived 'reverberations' of sensory-motor regions, which are irrelevant for lexico-conceptual processing. Our results speak against these claims. Our data are not merely correlational, because they demonstrated a causal link between the human motor cortex and the ability to memorize action sentences. Also, the embodied effects were not short-lived, because they extended to a delayed memory task.

We propose that a-tDCS – and, potentially, other protocols that could increase the excitability of the motor cortex, see below – improves performance in our task by enhancing the simulation of motor actions, which occurs while encoding action sentences (i.e., during the learning phase of the task). The selective enhancement simulation of action sentences caused by a-tDCS would result in stronger memory traces of the same sentences. However, we do not rule out that increased motor excitability may have also favored action simulation during the testing phase of our cued recall procedure. In keeping with our findings, recent behavioral studies using a similar task (Dutriaux et al., 2018; Dutriaux & Gyselinck, 2016) reported memory impairment for images and words denoting manipulable objects when participants assumed a posture that would potentially interfere with action simulation (hand behind the back). Taken together, these findings support the embodied cognition proposal that a high-level cognitive process, such as action language, is grounded in the sensory-motor system (Fischer & Zwaan, 2008; Glenberg et al., 2008; Glenberg & Kaschak, 2002). In other words, to understand words or sentences referring to actions, the simulation of the corresponding actions in the motor system contributes at least in part to comprehension and memory.

We have empirically demonstrated that the motor cortex is causally associated with memory of action-related meaning. Clearly, other neural structures might be additionally involved in processing linguistic meaning (e.g., in control monitoring, inhibition, semantic processing etc.), either because of cascade spread activation or because they play some functional role. Interestingly, Kemmerer et al. (2012) performed a large-scale neuropsychological study on 226 brain-damaged patients and reported that low performance in tasks requiring to process action language was most consistently associated with lesions occurring in left frontal areas (i.e., in the inferior frontal gyrus/anterior insula, ventral premotor cortex and M1). Poor performance was also associated with lesion of the left parietal (ventral postcentral and supramarginal gyri) and temporal areas (pMTG). Hence, because brain stimulation can exert its influence not only locally but also over interconnected brain regions (Polanía et al., 2018; Valchev et al., 2015, 2016; Zanon et al., 2018), it is possible that our a-tDCS protocol could have modulated not only M1 activity but also the activity of other sectors of the motor cortex overlapping with those documented by Kemmerer and colleagues and these regions could thus participate in the observed memory improvement (see the excellent review of Papeo et al. 2013 for a critical discussion on the issue). Regarding the last statement, modeling and neuroimaging studies support that M1 and other premotor areas are primarily modulated by tDCS. Computational modeling for a-tDCS with a 7 x 5 cm electrode (the same size as in the present study), placed on the left M1, shows that the most stimulated brain regions are anterior to the targeted M1, i.e., in the premotor cortex (Datta et al., 2009; Ho et al., 2016; Opitz et al., 2015). In keeping, fMRI measurements recorded while participants performed a motor task after receiving a-tDCS over M1, showed an increase in the activity of M1 and premotor areas (Jang et al., 2009; Stagg et al., 2009). These motor regions are also more functionally coupled after a-tDCS over M1, as suggested by resting-state fMRI (Polanía, Paulus, et al., 2011) and EEG (Polanía, Nitsche, et al., 2011).

The current results are compatible with hybrid proposals of semantic processing such as the Hub and Spoke theory (e.g., Lambon Ralph 2014). According to this theory, processing words activates highly distributed multimodal networks (spokes), including the motor system, as well as a transmodal semantic network (the hub) typically located in the bilateral anterior temporal lobes (ATL), which are responsible for integrative semantic processing. The functional role of the semantic hub has been supported by neuropsychological studies with semantic dementia patients, who suffer atrophy of the ATL and manifest dramatic impairment in semantic tasks (Hodges & Patterson, 2007). Also, applying inhibitory stimulation (1-Hz repetitive TMS) over ATL in neurotypical individuals induces difficulties in processing semantic information (Pobric et al., 2007, 2010). However, this approach leaves open the possibility that spokes such as the motor system can be part of the semantic machinery involved in linguistic meaning. Additional research will be needed to know how the motor cortex and ATL interact. In any case, whether the activation of the motor system precedes the activity of the ATL (García et al., 2019) or flows downstream from the ATL (Mahon & Caramazza, 2008), the issue of the functionality of the motor cortex requires empirical demonstrations beyond that of pure speculation. This study provides just such a demonstration.

Interestingly, Papeo et al. (2015) report that the activation of the motor cortex by action verbs is functionally dependent on the activity of the left pMTG, a region involved in the conceptual distinction between verbs and nouns. Papeo et al. (2015) applied inhibitory stimulation (1-Hz rTMS) over the pMTG and observed selective impairment in the semantic processing of verbs and, more relevant here, the elimination of the motor cortex modulation generally associated with action verbs. Again, our proposal is compatible with the above results. Even if the activation of pMTG precedes (and modulates) the activation of the motor cortex during processing of action language, this does not necessarily relegate the latter activation to the category of a simple epiphenomenon. That being the case, exogenous manipulation of M1 should not affect performance in our task. Thus, because we found that a-tDCS over M1 enhanced the recall of action language, we conclude that the motor system provides signals that are functionally relevant to performing our task. The current study clearly reinforces the idea that, at some stage, the motor system can play a crucial role in memory for action-related language.

A semantic theory of linguistic meaning should be able to accommodate the current evidence or accept that at least in some cases embodied representations are causally involved in the recall of action language. Note that our embodiment approach is not reductionist; namely, we do not imply that semantic representations are purely motor in action language. That is, having demonstrated the causal role of the motor system in action language does not preclude that other networks (semantic, visual, executive control) could also cooperate to produce meaning or memorize it. Yet, our results also indicate that a purely semantic reductionist approach (proposing that meaning exclusively relies on the amodal ATL activity, and cascading activations to sensory-motor networks are epiphenomenal) does not work either.

Previous studies focused on online embodiment effects, such as how inhibiting M1 affects online comprehension of action language (Gerfo et al., 2008; Kuipers et al., 2013; Repetto et al., 2013; Vukovic et al., 2017) or, alternatively, how comprehension of action language modulates online motor excitability (Buccino et al., 2005; O. Hauk et al., 2008; Oliveri et al., 2004; Papeo et al., 2009; Scorolli et al., 2012). By contrast, here we were particularly interested in testing long-term effects of embodied processes beyond the online effects of comprehension on motor excitability. Consequently, we demonstrated that exciting M1 improved action language recall, but we did not directly test whether comprehension was also improved. It is quite likely, however, that the impact of a-tDCS improved both comprehension and memory. First, the sentence-reading phase was under the influence of a-tDCS as much as the retrieval phase; second, the two processes are functionally related: understanding seems necessary for a cued-memory task like the one used here, which cannot be easily accomplished with shallow processing of language. Concerning the possible use of offline memory strategies by the participants (e.g., mental rehearsal, mental imagery) it was minimized by the presence of a distractive task between the learning and the retrieval phase. However, given the fact that we did not explore the chronometry of motor activations during comprehension, we cannot rule out that certain strategic activities can be carried out immediately after comprehension and, if so, they also were improved by excitatory stimulation of M1.

Although behavioral outcomes of brain stimulation are fundamental to inferring causal links between brain structure and functions, they cannot explain the neural mechanism underlying the functional improvement (Avenanti, Candidi, et al., 2013; Polanía et al., 2018; Silvanto & Pascual-Leone, 2012; Valchev et al., 2015, 2016). To provide insights on this matter, we monitored the motor excitability using MEPs and tested whether the neurophysiological changes induced by tDCS predict task performance. As expected, we found that the majority of participants in the experimental group showed increased MEP amplitudes after a-tDCS, whereas participants in the control group showed more variable MEP change following c-tDCS and no net physiological change. We leveraged MEP variability in the two groups to explore the relationship between physiological and behavioral changes. We highlighted a clear relationship between the two, suggesting that relative increase and decrease of motor cortex excitability could impact on action-specific memory performance. Regression analysis showed two additive effects, with the best predictor of memory performance being the factor Group (larger behavioral improvement following a-tDCS than following c-tDCS) and the second predictor being the normalized MEP index (larger behavioral improvement associated with increased motor excitability across groups), thus confirming and expanding the results of the main ANOVA. No interaction between these two predictors, suggesting a similar relationship between physiological and behavioral changes in both the experimental and the control groups.

Thus, two sources of variability appear to affect behavioral data in our study. Overall, a-tDCS appears better suited than c-tDCS for optimizing memory of action sentences, as shown by the effect of group. However, the additive linear relationship between neurophysiological and behavioral data supports the hypothesis that both protocols could affect performance also depending on their effectiveness in driving changes in motor excitability, with larger excitatory modulations associated with relative action-specific improvements and larger motor inhibition associated with relative action-specific impairments. This hypothesis is also in line with the observation that low-frequency rTMS over M1 –a supposedly ‘inhibitory’ TMS protocol (e.g., R. Chen et al., 1997)– decreased action language performance in morphological and semantic tasks (Gerfo et al., 2008; Repetto et al., 2013). These findings suggest that increased and decreased motor cortex excitability reflects a mechanism for enhancing and hindering action simulation which, in turn, could be responsible for the change in performance with action language comprehension and recall in previous research (Gerfo et al., 2008; Repetto et al., 2013) and the present work.

We observed no effect of c-tDCS at the group level, showing that the after-effects of a-tDCS are polarity-specific. Is the absence of c-tDCS effect on recall a methodological artifact? Perhaps the c-tDCS was inefficient because the participants’ overall performance in the memory task was quite poor, causing a floor effect. Yet, this interpretation is unlikely, since previous studies with materials and procedures similar to those employed here reported impaired recall due to a disruptive posture of the hands during learning in spite of the low memory performance in the baseline condition (Dutriaux et al., 2018; de Vega et al. submitted). A better explanation comes from the neurophysiological measure recorded here. In line with the variability reported in previous studies (e.g., Wiethoff et al. 2014; Jamil et al. 2017), c-tDCS at 2mA showed a variable pattern of change in motor excitability. Such physiological variability may explain the absence of a clear behavioral effect of c-tDCS. While in the present research c-tDCS parameters were selected as a control for the main experimental manipulation (a-tDCS), future studies could investigate a potential interference effect of c-tDCS, using a more reliable inhibitory protocol (e.g., 1 mA) in a language memory task like the current one.

This research has clear translational implications. There is evidence that patients with motor disorders (e.g., Cardona et al., 2013; García et al., 2017; Kargieman et al., 2014), especially those with Parkinson's disease (Abrevaya et al., 2017; Birba et al., 2017; García & Ibáñez, 2018; Herrera & Cuetos, 2012; Melloni et al., 2015), have a selective impairment in the processing of action-related language. Here we reported that a-tDCS applied over M1 in healthy participants selectively improved their performance in an action-related language task. This opens the possibility of applying a-tDCS or other excitatory brain stimulation protocols to help Parkinson’s patients to overcome their specific language deficits.

In conclusion, our study demonstrates that a-tDCS administrated over the left M1 improves the recall of manual action sentences, but not of attentional sentences. This improvement appears specific to a-tDCS, as it was not shown following c-tDCS. However, both protocols induced variable physiological changes, and action-specific memory improvements were not only predicted by the stimulation protocol (larger improvements following a-tDCS than following c-tDCS) but also by the induced physiological changes, with greater excitatory modulations of the motor cortex associated with larger behavioral improvements and relative inhibitory modulations associated with reduced action language performance. These findings provide causal evidence that the motor system is essential for efficient memory of action language.

Objectives and hypotheses of Experiment 2

Objective 1: Provide further evidence of the “disembodied” effect of negation in the motor system.

Hypothesis: Processing negative action language will reduce motor excitability compared to the affirmative action sentences.

Objective 2: Assess the crucial role of the inhibitory mechanism of response in the “disembodied” effect of negation.

Hypothesis: Disrupt the activity of a key region of the inhibitory control network, will suppress the effect of negative action language in the motor system.

Objective 3: Investigate at what phase of meaning process the negation effect occurs.

Hypothesis: The negation effect will take place at the initial stage of semantic sentences process, that is the integration with the verb.

Chapter 4: Experiment 2

The neural inhibition network is causally involved in the disembodiment effect of linguistic negation

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Abstract

Negation applied to action contexts reduces the activation of the motor system. According to the Reusing Inhibition for Negation (RIN) hypothesis, such "disembodiment" effect occurs because understanding negations engages the reuse of inhibitory control mechanisms. Here, we investigated whether the right inferior frontal gyrus (rIFG) – a key area of the inhibitory control system – contributes to primary motor cortex (M1) processing of negated action-sentences. Using a perturb-and-measure paradigm, we applied off-line low-frequency repetitive TMS (rTMS) over the rIFG, before performing a reading task involving action and attentional sentences presented in both affirmative or negative form. During the reading task, motor excitability was assessed by recording motor-evoked potentials (MEPs) induced by single-pulse TMS (spTMS) over the left M1, at two loci in the sentence: the verb or the object. Results show that after sham stimulation (baseline), motor excitability measured on the verb, was reduced for negative, compared to affirmative action sentences. Crucially, neuromodulation of rIFG suppressed this inhibitory effect of negation, since motor excitability was equaled for negative and affirmative action sentences. As expected, no effect of negation was observed for attentional sentences or when the pulse was delivered over the object. Our study confirms that understanding negative action sentences inhibits M1. This effect took place at an early stage of semantic processing (i.e., while processing the verb in our task), and faded at a later time-point. Critically, by highlighting a causal role of rIFG in this motor inhibition, we provide direct neurophysiological support to the RIN hypothesis.

Keywords: Embodied cognition, negation, action-language, inhibition, transcranial magnetic stimulation

4.1 Introduction

Embodied cognition theories of meaning postulate that the comprehension of action-related language involves the same sensory-motor circuit activated during the execution of the action being described (Barsalou et al., 2008; Fischer & Zwaan, 2008; García & Ibáñez, 2016; Glenberg et al., 2008). Notably, extensive empirical evidence from behavioral (de Vega et al., 2013; Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006), neuroimaging (Aziz-Zadeh et al., 2006; de Vega et al., 2014; Raposo et al., 2009; Tettamanti et al., 2005), EEG (Moreno et al., 2013, 2015; van Elk et al., 2010) and brain stimulation studies (Buccino et al., 2005; Oliveri et al., 2004; Papeo et al., 2009; Vitale et al., 2021) have shown that action-related words or sentences activate sensory-motor brain regions to simulate the referred action. However, negation seems to block the conceptual representation of the language meaning, leading to a “disembodiment” effect, which is reflected by the reduction of the motor system activation.

Neuroimaging studies, supporting the disembodiment effect of negation, first reported that processing negative action-language reduced the activation of motor and premotor circuits compared to affirmative action-language (Tettamanti et al., 2008; Tomasino et al., 2010). The negation effect on motor system was confirmed by subsequent behavioral studies with dual task paradigms like sentence-action interference (Aravena et al., 2012; Bartoli et al., 2013) and word typing paradigms (García-Marco et al., 2019), reporting less involvement of motor cortex activation for negative action sentences than for their affirmative counterpart. Moreover, physiological measures obtained with non-invasive brain stimulations techniques revealed that negation selectively modulated motor cortex excitability for the sentences with manual content, but no for the sentences with an abstract content (Liuzza et al., 2011; Papeo et al., 2016). Additionally, Papeo et al. (2016), by means of chronometric TMS, reported the difference in motor excitability between affirmative and negative sentences occurs as soon as 250 ms after the verb onset, corroborating the disembodied idea whereby the access to the simulation of a negated meaning is detained.

Which is the neural mechanism underlying the processing of negation and leading to the reported reduction of motor activity? Recently, the Reusing Inhibition for Negation (RIN) hypothesis has been proposed, which states that the comprehension of negation reuses the neural circuits of the inhibitory control mechanism (Beltrán et al., 2018; de Vega et al., 2016; Liu et al., 2020). Indirect evidence supporting the RIN hypothesis comes from studies with EEG measures recorded in dual task paradigms in which a Go/No Go task is inserted in a sentence comprehension tasks. The results showed reciprocal effects between inhibition (NoGo trials) and negation; that is, negated action sentences reduced power of fronto-central theta oscillations, a robust index of neural inhibitory activity, in subsequent NoGo trials (de Vega et al., 2016), while pre-setting an inhibitory state in preceding NoGo trials affected the modulation of the subsequent waveform for negated action sentences compared to their affirmative counterparts (Liu et al., 2020). In the same way, Beltrán et al. (2018) reported that, the comprehension of negative manual-action sentences, combined with a Stop-Signal task leads to enhancement of the inhibition-related N1 component and increment of stop reaction time in comparison with their affirmative counterparts. Critically, the common estimated source of such effects was found in the right inferior frontal gyrus (rIFG), a core region of the inhibitory control mechanism (Zhang et al., 2017; see Aron et al., 2014; Chambers et al., 2009 for review). Compatibly, negation imbedded in a manual-action context delayed typing execution of manual action verbs, suggesting the effector-specificity influence of the inhibitory mechanism (García-Marco et al., 2019). Furthermore, in the Experiment 2 of Papeo et al. (2016), the cortical silent period, an index of GABAergic inhibitory neurons activity, increased for negative action-verbs processing relative to affirmative action-verbs.

As mentioned above, rIFG – particularly, the pars opercularis – seems to play a crucial role in response inhibition. It has been demonstrated that patients with damage of rIFG and “virtual lesion” induced in healthy participants through repetitive TMS (rTMS) presented slower stop reaction time compared to the control group (Aron et al., 2003; Chambers et al., 2006, 2007). Based on these results, Aron proposed that rIFG is the key component of a brain network, mainly lateralized in the right hemisphere, which orchestrates the balance between excitation and inhibition, sending inhibitory signals to the motor cortices through fronto-striatal-thalamic circuit during tasks demanding response inhibition (Aron, 2011; Chambers et al., 2009). Then, it is appropriate to hypothesize that rIFG might be responsible for the motor cortex inhibition typically observed for negative action-related sentences, compared to their affirmative counterparts. However, although the aforementioned studies strongly support the RIN hypothesis, they only provide correlational evidence, failing to demonstrate the functional connection between the inhibitory system and the reduction of activation in the motor system during the process of negative action sentences.

One way to directly assessing whether the inhibitory control area is causally involved in the comprehension and motor mapping of negated action-language is through a perturb-and-measure stimulation protocol combining offline low-frequency rTMS and recording motor evoked potential (MEP) induced by single pulse TMS (spTMS) on M1 (Avenanti et al., 2007; Avenanti, Annella, et al., 2013; Papeo et al., 2015). The rationale of this refined method is to transiently inhibit neural activity in a target area and test the remote effects of such perturbation on task-related modulations of M1 excitability, demonstrating in this way a causal link between the targeted area and the functional (e.g., language-related) modulation of M1. Here, we employed this method for the first time to provide evidence for the causal role of the inhibitory system in negation processing, thereby providing unprecedented neurophysiological evidence supporting the RIN hypothesis. To this aim, we perturbed the activity of the rIFG, a key region of the response inhibition mechanism, to assess the consequent modulation of the M1 corticospinal excitability during comprehension of affirmative and negative action sentences. In a group of participants, we administered low-frequency rTMS over the rIFG to transiently inhibit this region, whereas in another groups of participants we administered off-line sham stimulation on vertex, as a control (baseline) condition. In both groups, following the stimulation session, we recorded electromyographic (EMG) activity of a target hand muscle in response to spTMS over M1 during a reading task in which participants were presented with affirmative and negative action and attentional sentences. In normal physiological conditions (i.e., following sham rTMS) we expect to find a reduction of MEP amplitudes for negative action sentences compared to affirmative action sentences and to attentional sentences (Papeo et al., 2016). Crucially, we expect that active rTMS on rIFG would prevent the inhibitory effect of negative action sentences to emerge. That is, we expected no difference between sentence types following rIFG-rTMS, a result that would provide direct evidence of functional role of rIFC in the M1 modulation associated with the comprehension of negated action sentences. If so, this would support a strong prediction of the RIN hypothesis.

Additionally, in the sham group we were interested in verifying whether the inhibitory effects of negation were strictly linked to the verb, or if they were prolonged to a later stage of sentence processing, namely, in the integration of final object noun. Therefore, we used relatively more complex sentences than in previous studies (i.e, *Ahora no agarrarás un cascanueces / Now you will not catch a nutcracker*), and delivered the spTMS either over the verb or over the noun. If the negation induces a disembodied effect in the motor system at an initial stage of meaning construction, then we hypothesized to find a selective effect of negation on motor excitability for action contents when the spTMS is applied at the verb locus. On the contrary, if the disembodied effect of negation for action contents is observed when the spTMS pulse is delivered over the noun, this would indicate that the negation effect lasts until the final stage of the semantic integration process.

To summarize, this study aims to: 1) replicate the disembodiment effects reported by Papeo et al. (2016, Exp.1); 2) examine the time course of the negation effect, testing two loci in the sentences: the verb and the noun; 3) and more importantly, assess for the first time if the inhibitory system (rIFG) is causally involved in the processing of negative action sentences, acting on M1.

4.2 Method

4.2.1 Participants

Sixty-four healthy participants took part in this study. They were randomly assigned to two stimulation groups: 32 participants (8 men, mean age ± SD: 20.6 years ± 2.7) were assigned to the sham rTMS group and 32 participants (6 man, mean age ± SD: 23.5 years ± 4.0) were assigned to the active rTMS group. All participants were right-handed, had Spanish as their mother tongue, and did not report any neurological disease, visual problems, or drug intake. All students gave informed consent and received course credit for volunteering. The Research Ethics Committee of the University of La Laguna approved this study and the experiment was conducted according to the principles expressed in the Declaration of Helsinki. One participant belonging to the sham rTMS group was discarded from the analysis due to recording failure.

4.2.2 Linguistic Material

Verbal stimuli were presented on a 23-inch screen located about 80 cm away from the participant. Two sets of 240 Spanish sentences were used. The lexical material was adapted from a previous study (Vitale et al., 2021), and included 30 manual action verbs, 30 attentional verbs, and 120 nouns referring to manipulable objects. Every sentence (displayed with character height of 36pt in Courier New font size) started with the temporal adverb “ahora” (now) followed by the polarity word, then the verb appeared followed by the article and finally by the noun. Each sentence was presented in an affirmative and a negative version (Table 4.1), resulting in a total of 60 affirmative action sentences, 60 negative action sentences, 60 affirmative attentional sentences and 60 negative attentional sentences for each set. Within each set, each verb appeared in two sentences combined with different objects, and the sentences in the two sets differed in the combination of nouns and verbs in such a way that if a given noun appeared with a manual verb in set 1 (e.g., *Ahora sí apretarás un tornillo* / now you will [yes] tighten a screw), it was associated with an attentional verb in set 2 (e.g., *Ahora sí distinguirás un tornillo* / now you will [yes] distinguish a screw) and vice versa. The material was previously validated using lexical values downloaded from the EsPal database and testing a group of 30 participants not taking part to the present study (see Vitale et al., 2021 for details), ensuring no differences in frequency, length and familiarity between the action and attentional verbs (See Table 4.2).

Action sentences

Affirmative: *Ahora* ***sí*** *agarrarás una tenaza* / now you will [yes] grab a pliers

Negative: *Ahora* ***no*** *agarrarás una tenaza* / now you will not grab a pliers

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Attentional sentences

Affirmative: *Ahora **sí** apreciarás un libro /* now you will [yes] appreciate a book

Negative: *Ahora **no** apreciarás un libro /* now you will not appreciate a book

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Table 4.1. Example linguistic material

	Manual action verbs	Attentional verbs	t	p-level
Frequency	23.83 ± 54.91	56.84 ± 93.87	-1.66	0.10
Length	6.67 ± 1.37	7.27 ± 1.87	-1.41	0.16
Familiarity	6.24 ± 0.52	5.97 ± 0.76	1.55	0.13

Table 4.2. Values of linguistic variable: frequency and length values were obtained from the EsPal database. To evaluate the familiarity of the verbs, a behavioural study of 30 participants were conducted where they had to evaluate on a 7-point Likert scale the familiarity of each verb. Mean values were calculated, and t-tests were conducted for every variable, ensuring no differences between the two type of verbs.

4.2.3 TMS and electromyography recordings

To assess language-related modulation of M1 excitability we administered spTMS over the left M1 using a Magstim 200 magnetic stimulator (Magstim, Whiteland, Dyfed, UK) connected to a figure-of-eight magnetic coil (70 mm outer diameter; peak magnetic field 2.2 Tesla) and recorded TMS-induced MEPs from the contralateral right first dorsal interosseous (FDI) using a Biopac MP-35 (Biopac, U.S.A.) electromyography (EMG) system. Surface EMG was recorded from the right FDI with Ag-AgCl electrodes placed in a belly-tendon montage with the ground electrode on the right wrist. EMG signals were band-pass filtered (30-500 Hz), sampled at 5 kHz, digitized and stored on a computer for offline analysis. The TMS coil was held tangentially to the skull, with the handle pointing backward and laterally at 45° from the midline, resulting in a posterior–anterior direction of current flow in the brain. The optimal coil position on left M1 was defined as the point where stimulation consistently evoked the largest MEPs in the right FDI. During the experimental session, TMS intensity was set at 120% of the resting motor threshold (rMT), which was defined as the lowest intensity of output that evoked five small responses (~50μV) in the relaxed FDI muscle in a series of 10 stimuli (Rossini et al., 2015). Mean motor thresholds (± standard deviation) were 37.3% ± 5.8 and 38.8% ± 4.4 of the maximum stimulator output in sham and active rTMS groups, respectively, and did not differ between groups (t_{31}= -1.51, p = 0.14).

4.2.4 rTMS parameters and site localization

To perturb rIFG we administered image-guided rTMS using a figure-of-eight coil (70 mm diameter) connected to a Magstim Rapid2 stimulator (Magstim, Whiteland, Dyfed, UK). During active stimulation, the coil was placed tangentially over vertex with the handle in an upward vertical orientation. During sham rTMS, the coil was tilted at 90° over the vertex, in order to provide some scalp sensations and a similar "clicking" sound, without inducing a current in the brain. Before each spTMS session, 15 minutes of offline repetitive low-frequency (1Hz) stimulation at an intensity of 90% of the rMT (see above) was administered. Stimulation site were localized using the BrainSight frameless stereotaxic system (Rogue Research, Canada) with a Polaris (NorthernDigital, Canada) infrared tracking system to measure the position of anatomical landmarks on each participant's head. Prior to the neuronavigation session, for each participant, high-resolution T1 weight anatomic images were acquired with a 3T GE Sigma Excite MRI scanner at the Magnetic Resonance Service for Biomedical Research, at the University of La Laguna (TR = 4.768 ms, TI = 650, TE = 1, 9, flipangle:20, voxelsize;1.02 × 1.02 × 1, matrix 228 × 228, FOV26 × 26, slice order: sequential, gap: 0) and prepared for the neuronavigator. Then, for each magnetic resonance image (MRI) scan, several anatomical landmarks were marked (tip of nose, left and right intra-tragus notches). Another infrared tracker was placed over the TMS coil to identify the scalp point where the target was selected in the MRI image and to mark the point on the cap. Each participant's MRI was compared to a normalized space so that TMS coordinates used were identified in a standard space. The rIFG target location was based on previous fMRI meta-analysis (Zhang et al., 2017) exploring the activation of inhibitory control on action withholding and action cancellation and rTMS studies (Chambers et al., 2007; Verbruggen et al., 2010) that provide consisting evidence of the crucial role of rIFG in cancelling a motor response. The stimulation site, set on the following MNI coordinates: x = 53, y = 16, z = 17, corresponded to the rIFG *pars opercularis*, and it was targeted in a locus anterior to the precentral sulcus, between the lateral sulcus and inferior frontal sulcus (Chambers et al., 2007; Verbruggen et al., 2010).

4.2.5 Procedure

The experiment consisted of two separated sessions. In session 1, the structural MRI images from each participant were acquired. In session 2, coil position for M1 and stimulation intensity was established by determining participants' M1 hotspot and rMT, and coil position for the target rTMS site (rIFG) was localized by means of individual anatomical images fed in the neuronavigation (see above). Afterwards, participants received 15-minutes of sham or active rTMS over the target site, immediately followed by the language comprehension task combined with the spTMS stimulation. The task consisted of 4 blocks of 30 trials taking ~ 15 minutes, thus falling within time window where rTMS effects can be observed (Avenanti et al., 2007, 2012; R. Chen et al., 1997; Münchau et al., 2002; Serino et al., 2011). After a 5-min rest period, a second 15-min application of sham or active rTMS stimulation – identical to the one previously received – was administered (Goldsworthy et al., 2015; Nyffeler et al., 2006; Terranova et al., 2019). Then, the participants executed 4 additional blocks of 30 trials of the language task and spTMS. Two blocks of 20 MEPs - which served as baseline - were collected using spTMS, before and after the stimulation session. The structure of the sessions is shown in Figure 4.1A.

The experiment was programmed using E-Prime software to control sentences presentation and to trigger TMS pulses. Each trial consisted of a sentence, with verbal material presented word by word which started with a 200-ms fixation cross, followed by the temporal adverbial appearing for 200 ms. After that, the polarity operator was presented for 200-ms and then the manual or attentional verb was shown for 300 ms. Successively, the article appeared for 200 ms followed by the noun showed for 300 ms. The words presentation was separated by an interval of 200 ms (see Figure 4.1B). In half the trials, the spTMS pulse was delivered at 250 ms of verb onset, while the remaining trials the pulse was delivered at 250 ms of noun onset. Finally, a whole sentence was displayed on the screen that could be the same of the one presented previously one word a time, or differed in some segment of the sentence (e.g., the polarity operator, the verb or the object). Participants had to verbally respond “yes” when the sentence matched the previous one, and “no” when the sentences differed from each other. An experimenter collected the answers by pressing a computer key. In order to avoid changes in motor excitability due to verbal response (Meister et al., 2003; Tokimura et al., 1996), participants were instructed to answer 2-3 seconds after the final sentence was presented. Moreover, to avoid changes in motor excitability due to TMS per se, after the response a white screen appeared for 3-5 sec thus ensuring an inter-pulse interval of about 10 sec (R. Chen et al., 1997).

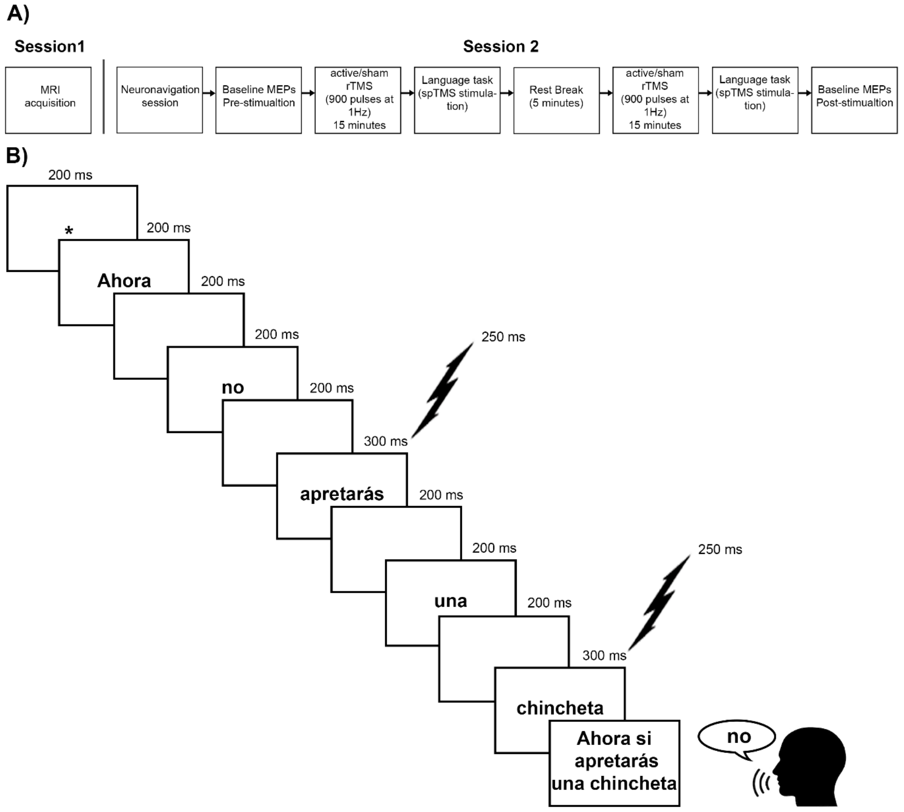

Figure 4.1. Structure of experimental procedure. (A) Schematic representation of the experimental sessions. (B) Example of a trial sequence (translation: Now you will not press a thumbtack).

4.2.6 Data analysis

Neurophysiological and behavioral data were processed offline. To corroborate that there was no difference in the accuracy between the groups, a four-way mixed factors ANOVAs with Group (sham rTMS and active rTMS) as between subjects' factor and Locus of stimulation (verb and object), Type of sentence (action and attentional) and Sentence polarity (affirmative and negative) was conducted on the percentage of corrected answers. One participant was eliminated from further analysis due to the high percentage of incorrect responses, which deviated from the mean by 2SD.

MEPs were measured in mV and computed as the median peak-to-peak amplitude for each condition. MEPs associated with an incorrect answer, were excluded from the analysis (less than 5% in both group). Additionally, MEPs preceded by background EMG deviating from the mean by more than 2 SD were removed from the analysis (less than 5% in both group), since it is known that EMG background can affect motor excitability (Devanne et al., 1997). To normalize the data distribution, a logarithmic transformation was applied to the MEP values [log (median MEP amplitude value +1)]. Normalized MEPs were analyzed by means of a four-way mixed factors ANOVA with Group (sham rTMS and active rTMS) as between subjects' factor, and Locus of stimulation (verb and object), Type of sentence (action and attentional) and Sentence polarity (affirmative and negative) as within subject factor. In all ANOVAs, post-hoc comparisons were performed using the Duncan's test. Partial eta^2 (η_p^2) was computed as a measure of effect size for the main effects and interactions, whereas repeated measures *Cohen's d* was computed for post-hoc comparisons (J. Cohen, 1992). To detect the presence of outlier, two Cluster analysis were conducted separately in each Group. The Cluster analysis revealed the presence of four outliers (2 for the sham rTMS group and 2 for the active rTMS), which were removed from all the analysis.

4.3. Results and Discussion

4.3.1 Accuracy

Task accuracy was high in both groups (percentage of mean correct answers ± S.D.: sham rTMS: 96% ± 3; active rTMS: 97% ± 2). The Group x Locus of stimulation x Type of sentences x Polarity ANOVA conducted on accuracy showed no main effect or interaction (all $F < 2.04$; $p > 0.16$), confirming similar accuracy on performance across the two groups and all the experimental conditions.

4.3.2 MEPs

The ANOVA Group x Locus of stimulation x Type of sentences x Polarity conducted on normalized MEPs, showed a significant Locus of stimulation x Type of sentences interaction ($F_{1,56} = 4.74$, $p = 0.03$, $\eta_p^2 = 0.08$) and a marginally significant 4-way interaction ($F_{1,56} = 2.80$, $p = 0.099$, $\eta_p^2 = 0.05$). Because of the theoretical relevance of such marginal trends, to better investigate the temporal dynamics of negation effect we performed separate Group x Type of sentences x Polarity analyses for the verb and for the object locus. In keeping with previous studies (Buccino et al., 2005; Liuzza et al., 2011), the ANOVA performed in the verb locus showed a strong main effect of Type of sentences ($F_{1,56} = 7.14$, $p < 0.01$, $\eta_p^2 = 0.11$), accounted for by higher MEPs amplitude for the attentional sentences (mean MEP amplitude ± SD: 0.354 ± 0.153) compared to action sentences

(0.345 ± 0.150), confirming the embodiment prediction, according to which sensory-motor simulations contribute to action-language processing (Barsalou et al., 2008; Fischer & Zwaan, 2008; García & Ibáñez, 2016; Glenberg et al., 2008). More importantly, the three-way Group x Type of sentences x Polarity interaction was also significant ($F_{1,56} = 4.54$, $p = 0.04$, $\eta_p^2 = 0.08$). To further explore such interaction, separate Type of sentences x Polarity ANOVAs were performed for the sham rTMS group and for the active rTMS group. The ANOVA on the sham group maintained the main effect of Type of sentences ($F_{1,28} = 5.35$, $p = 0.03$, $\eta_p^2 = 0.16$), indicating a decrease in motor excitability for manual action sentences (0.360 ± 0.124) relative to attentional sentences (0.372 ± 0.125). Most relevant, the interaction Type of sentences x Polarity was also significant ($F_{1,28} = 6.05$, $p = 0.02$, $\eta_p^2 = 0.18$), driven by a reduction in MEPs when processing negative action sentences. Indeed, post hoc analysis showed lower MEPs amplitude recorded while reading negative action sentences (0.354 ± 0.121) compared to affirmative action sentences (0.367 ± 0.129, p = 0.046, *Cohen's d* = 0.11), to affirmative attentional sentences (0.36 ± 0.134, p = 0.045, *Cohen's d* = 0.11) and to negative attentional sentences, (0.377 ± 0.119, $p < 0.01$, *Cohen's d* = 0.19) (see Figure 4.2A). The decrease of MEPs amplitudes for negative action sentences in the sham group is in line with previous studies (Aravena et al., 2012; Bartoli et al., 2013; Beltrán et al., 2018; de Vega et al., 2016; García-Marco et al., 2019; Liu et al., 2020; Liuzza et al., 2011; Papeo et al., 2016; Tettamanti et al., 2008; Tomasino et al., 2010), reporting a reduction of motor brain activity associated with negative action-related language. Particularly, we replicated the results of Papeo et al. (2016), showing that the polarity context (affirmative or negative), already modulates the motor cortex excitability at the time of verb presentation. Taken together, these findings confirm that the disembodiment effect of negation occurs at the initial stage of sentence integration processing (see Papeo et al., 2015); that is, once the negation is semantically integrated with the verb, it immediately interferes with the embodied representation, leading to the observed disembodiment.

Nonetheless, the major novelty of our study was to test how the intervention on the inhibition system affects the processing of negative action sentences. We found that the disturbance of the rIFG activity by means of active low-frequency rTMS resulted in the absence of significant effects of polarity or its interaction (all $F < 2.06$; all $p > 0.16$), which confirms that rIFG plays a crucial influence on the deactivation of the motor system during the processing of negative action sentences. In fact, according to our prediction, inhibiting of rIFG disrupts the reduction of motor excitability in negative action sentences as reflected by the null effects on MEPs. By showing that rTMS hindered the functional modulation of M1 excitability when processing negative action sentences, we provided the first neurophysiological evidence that the brain inhibition system is causally involved in the disembodiment effect of negation, thus supporting the RIN hypothesis. These findings go beyond the correlational evidence provided elsewhere by the results of behavioral studies (García-Marco et al., 2019), spTMS (Liuzza et al., 2011; Papeo et al., 2016) and EEG studies (Beltrán et al., 2018; de Vega et al., 2016; Liu et al., 2020).

Finally, the ANOVA conducted on the object locus did not show any significant result (all $F < 1.93$; all $p > 0.17$) (Figure 4.2B), indicating that the negation effect was bounded to the verb, and did not extend to the next stage of the semantic process.

The inhibitory circuit is constituted by several brain regions – including the rIFG, dorsolateral prefrontal cortex, pre-supplementary motor area, anterior cingulate cortex and the striatum-subthalami nuclei. According to the model proposed by Aron (2011), the rIFG plays a major role in this network, implementing stopping signals to the motor system through the striatum-subthalamic nucleus pathways (Aron, 2011; Chambers et al., 2009), or, possibly, directly to M1 (Neubert et al., 2010). Our results suggest that this neural inhibition model can be extended to linguistic negation, consistently with the RIN hypothesis. That is, in brain normal states (in sham rTMS) the rIFG would be recruited by negative action statements to inhibit, through direct cortico-cortical or striatum pathways, the motor cortex, resulting in the disembodiment effects of negation obtained here and elsewhere (Aravena et al., 2012; Bartoli et al., 2013; de Vega et al., 2016; García-Marco et al., 2019; Liuzza et al., 2011; Papeo et al., 2016; Tettamanti et al., 2008; Tomasino et al., 2010). However, the disturbance of rIFG activity (in active rTMS) blocks the inhibitory signals at M1, and the motor excitability for negative action sentences becomes similar to that of affirmative sentences.

Although our study clearly indicates a functional influence of rIFG on M1 during the comprehension of negated action sentences, future studies are needed to further test the RIN hypothesis by focusing on the causal involvement of other key nodes of the neural network supporting inhibitory control such as the pre supplementary motor area (pre-SMA) (Borgomaneri et al., 2020; Zhang et al., 2017). Moreover, to address neuroanatomical specificity of the findings, further studies will need to include active rTMS on control areas outside the inhibitory control network (e.g., the occipital cortex). In the latter case, a physiological effect similar to that observed for our sham group would be expected, and this would provide supplementary support to the hypothesis that inhibitory control mechanism is responsible for the reduction of motor activity for negated action-languages.

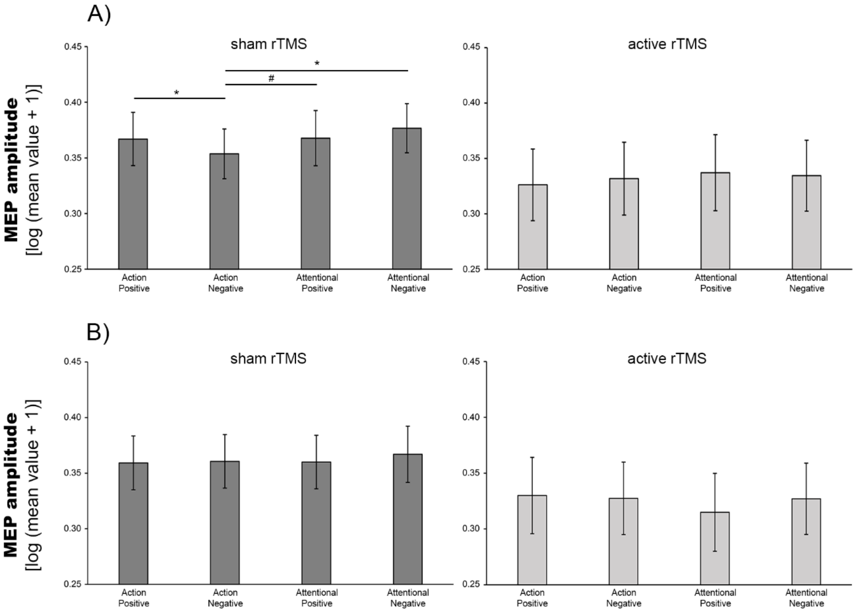

Figure 4.2. MEPs modulation as a function of type of sentence (action vs. attentional) and polarity (affirmative vs. negative) for the verb locus (A) and for the object locus (B).

4.4 Conclusion

In conclusion, our study shed new light on the effect of negation on the motor system. In keeping with the disembodied view, we showed that negation, imbedded in an action context, blocked the simulation of the meaning representation expressed in the sentences (de Vega et al., 2013; Papeo et al., 2016). More relevant, we found that this “disembodiment” effect of negation is caused by the activation of the inhibitory system, supporting the RIN hypothesis.

Chapter 5:

General discussion

The basic tenet of the embodiment approach to language is that the comprehension of words and sentences may require internal sensory-motor simulations of the referred objects or events. Such assumption implies that to understand action-related language, the activation of the motor cortices is necessary. An objective of this thesis was to provide direct empirical evidence that the embodied simulations are functionally involved not only in the comprehension of action language, but also in long-term memory. A second objective was to shed light on the neural mechanisms responsible for the disembodiment effects of linguistic negation on action language. In two experiments, we used different non-invasive brain stimulation protocols which are particularly appropriate for drawing causal conclusion on the neural mechanisms underlying embodiment and disembodiment effects.

The first experiment demonstrated the causal role of M1 in the memory for action language. In two different groups, we applied offline active (anodal or cathodal) or sham tDCS over left M1, before participants performed an action language memory task. The memory performance selectively improved for the action sentences after receiving a-tDCS, compared to sham stimulation, while no difference was shown for the attentional sentences. No similar effects were observed in the cathodal group. Moreover, to assess the effectiveness of the stimulation, we measured the physiological changes induced by the tDCS. Although the effect was variable in both groups, the increase of MEPs after a-tDCS was almost significative, while no net changes were detected after c-tDCS. Remarkably, across group, the increase in motor excitability positively correlated with the improvement in the memory performance. In other words, participants who showed bigger MEPs amplitude after active stimulation, reflecting an enhancement of motor activity, also showed higher action language memory performance.

The chapter 1 of the present dissertation extensively discusses data in favour of the EC approach to action language. As mentioned before, these studies predominantly contributed to assess how understanding of action language is associated with the activation of the motor cortex, but they did not answer the “necessity question”, that is, to what extent this activation is necessary for meaning. Indeed, only few studies used neuromodulation tools to investigate this issue (Gerfo et al., 2008; Gijssels et al., 2018; Kuipers et al., 2013; Liuzzi et al., 2010; Niccolai et al., 2017; Repetto et al., 2013; Vukovic et al., 2017; Willems et al., 2011), perturbing the activity in motor areas to observe behavioral effect on the understanding of action language. The current Experiment 1 contributes to verify the functional role of M1 in action meaning comprehension, adding some important novelties. First, rather than observing the impact of “virtual lesions” in M1 by means of an inhibitory protocol aiming to impair performance, we found that an excitatory stimulation protocol improved performance in memory for action-language. The result is compatible with previous studies that demonstrated how the enhancement of M1 activity improves the performance in implicit motor learning tasks (López-Alonso et al., 2015; Nitsche, Schauenburg, et al., 2003; Reis & Fritsch, 2011) and also in the speech domain (Buchwald et al., 2019). Here, the improvement of performance was observed in a long-term memory task that followed the processing of linguistic meaning. With these premises and considering the large literature supporting the EC view, the enhancement of M1 activity seems to reinforce the simulation of the action referred to in the sentence, which presumably occurs during the encoding stage (e.g., learning phase of the sentences), resulting in a stronger memory trace of the sentence. Still, we cannot exclude that the motor simulation also takes place in other stages of the task, such as recall.

Second, the performance measure employed here consisted of a cue-based memory test of simple sentences previously memorized, instead of online activation measures involving morphological, syntactic or semantic tasks. Therefore, this study has shown a specific long-term effect of the embodied mechanism, while most of the previous research focussed on embodiment effects during online comprehension of action language. Actually, it should be noted that the present task did not directly evaluate the involvement of M1 in action comprehension; however, enhancing action simulation (see above) is likely to lead not only to better performance on the memory task, but also to improved understanding of manual action sentences, since the two process are functionally related. This is especially true in a memory task like the one used here, in which the possible use of memory strategies was minimized by means of a distractive task preceding recall, and the performance in this task may be derived primarily from comprehension of sentences. Yet, there is still the possibility that some memory strategy takes place beyond the comprehension process and, therefore, additional investigation is necessary on the temporal dynamics of the motor system across the different stages of the task.

Finally, since the tDCS induced effects were measured not only on the behavioral performance, but also at physiological level, we have demonstrated for the first time that increased motor excitability is a predictor of improvements in action language memory. As regression analysis showed a higher increase in MEPs was associated with better memory performance. Importantly, another predictor of memory performance was the stimulation group, that is, the a-tDCS induced larger memory improvement compared to the c-tDCS. As expected, in the anodal group the increment of motor excitability was detected in the majority of participants (18 of 25), while the c-tDCS induced more variable results (13 of 25 showed MEPs decrease). Then, although the a-tDCS seems to be more effective compared to c-tDCS, the enhancement of motor activity induced by the stimulation predicts the consequent change in the behavioral performance. This result confirms the idea that when the active stimulation (especially anodal) enhances the activation of motor cortex, as measured by the increase of motor excitability, it reflects a mechanism that reinforces action simulation of the sentences, resulting in a better memory for action language.

Taking together, these results provide, for the first time, strong evidence for a causal link between the motor cortex and the memory for action related language, clearly supporting the embodied view on linguistic meaning. Against this claim, the critics of the EC approach to language suggest that the motor activation observed for action language is the consequence of the interface between the conceptual system, where all concepts are processed, and the sensory-motor system (Chatterjee, 2010; Mahon, 2015; Mahon & Caramazza, 2008). These theorists accept that the motor system is activated by action language, but they consider such effect as an epiphenomenal downstream activation occurring after the amodal representation, which constitutes the "real" meaning, was generated by the conceptual system. This proposal clearly opposes the idea of a necessary and functional role of motor network in the comprehension of action related language. The results of the first experiment of this dissertation contrast with this view, because they demonstrate the functional involvement of M1 in memorizing manual action sentences, suggesting that the motor system has a key role in action language and its activation is not merely collateral.

Experiment 2 of this dissertation aimed to investigate the paradoxical effect of negation reported in the embodiment literature: unlike in affirmative action sentences, which induce sensory-motor simulations, negation inserted in action sentences produces a "disembodied" effect, reflected in a reduction of activity on the motor areas (see chapter 2 for an extensive review). The RIN hypothesis posits that such effect occurs because the understanding of negation recruits the neural mechanisms of response inhibition (Beltrán et al., 2018; de Vega et al., 2016; Liu et al., 2020). To date, data supporting the RIN hypothesis come from correlational studies, confirming that the inhibitory system is activated during the processing of negated action sentences. However, these studies do not allow to conclude that the inhibitory mechanism plays a functional role in negation. For this reason, the second experiment aimed to directly test this assumption, by employing an innovative perturb-and-measure stimulation protocol. This method consists of disrupting the activity of a given area through offline low-frequency rTMS and evaluate the effect of this perturbation on motor excitability, recording MEPs amplitude using sp-TMS. Specifically, in our second study we induced a "virtual lesion" on rIFG, a crucial region of the inhibition network (Aron et al., 2014; Chambers et al., 2009), and evaluate the consequence on the excitability of the left M1 while participants read action and attentional sentences, presented in both affirmative and negative form. In this way, we expected to demonstrate a causal relation between the activity of the inhibitory system and the processing of negative action sentences. In two stimulation groups, sham or active low frequency rTMS was delivered over rIFG before performing the linguistic task, during which MEPs were recorded in the left M1corresponding to the right hand FDI muscle. In addition, to verify the temporal dynamics of negation effect, sp-TMS pulses were delivered in two loci of the sentences: the verb and the object. In the sham group (baseline), the MEPs recorded for the verb loci were smaller during negative action sentences, relative to their affirmative counterpart and relative to both affirmative and negative attentional sentences. Crucially, perturbing rIFG activity via rTMS suppressed the disembodied effect of negation on the motor system, as shown by the absence of significant differences between affirmative and negative action sentences, confirming our prediction that the disembodied effect of negation in M1 is causally related to the activity of the rIFG.

The reduction in CSE specifically associated with negative action sentences observed in our sham condition was consistent with previous findings revealing "disembodied" effects of negation inserted in action sentences on the motor area activity (Aravena et al., 2012; Bartoli et al., 2013; Foroni & Semin, 2013; García-Marco et al., 2019; Liuzza et al., 2011; Papeo et al., 2016; Tettamanti et al., 2008; Tomasino et al., 2010). In particular, our sham condition replicated the study of Papeo et al. (2016) that showed a reduction in motor excitability, measure as MEPs amplitude, in response to sp-TMS, in negative compared to affirmative action sentences already at the initial phase of semantic integration processing (Papeo et al., 2015). In other words, there is evidence that as soon as negation marker is integrated with the action verb meaning, it reduced or blocked the simulation of the negated action, as reflected by the deactivation of motor activity.

However, the main objective of this second study was to test a radically new proposal, trying to reveal the neural mechanism causally responsible for the disembodied effect of negation. Our finding showed that perturbing rIFG abolished the inhibitory effect of negative action sentences on M1 activity, providing for the first time clear evidence on the functional role of the inhibition system in the processing of negation, and offering strong support to the RIN hypothesis, beyond previous correlational data (Beltrán et al., 2018; de Vega et al., 2016; García-Marco et al., 2019; Liu et al., 2020; Liuzza et al., 2011; Papeo et al., 2016). In the present experiment we chose the disruption of the rIFG activity, which is one of the main nodes of the inhibitory network. However, it is likely that the stimulation of other key regions of the inhibitory mechanism (e.g., SMA, see chapter 2) could also suppress the disembodied effect of negation. Future study should be conducted to investigate this aspect, in order to provide additional support for the RIN hypothesis.

The last point of this experiment to consider is the lack of significant effects for the MEPs when the spTMS was delivered during the object presentation. As we discussed before, this result suggests that the negation effect is linked to the initial stage of semantic process (the verb) and does not extend to the final phase of sentences comprehension.

It should be noted that this study presents one limitation. To definitely affirm that the negation effect relies exclusively on the inhibitory mechanism of response, another control area outside the inhibitory circuit should be perturbed and then evaluate its effect on motor excitability during the comprehension of negative action language. In the case of active stimulation of an additional control area, a similar modulation of CSE to the ones observed in our sham condition would be expected.

In conclusion, the novelty of the present dissertation, is the empirical demonstration of neural causality in two aspect of the embodied cognition approach to language:

1. The first study showed the crucial role of M1 in the memory for action language
2. The second study demonstrated the functional link between the inhibitory mechanism and the disembodied effect of negation.

Chapter 6:

Conclusions

The main conclusions of Experiment 1 (E1) and Experiment 2 (E2) in this thesis can be summarized as follows:

1) Enhancing the primary motor cortex (M1) activity, using offline anodal tDCS, improves performance on a memory task for action-related sentences, whereas no effect was observed for the attentional sentences (E1).

2) This selective improvement of memory for action sentences demonstrates that the motor cortex plays a functional (causal) role in the motor simulation of meaning of these sentences (E1).

3) The above results demonstrate for the first time that embodied representations have long term consequences, beyond the online effects frequently reported in the literature (E1).

4) The selective improvement in memory performance for action sentences is associated with the increased motor excitability induced by tDCS (E1).

5) Processing negative action sentences, compared to affirmative action sentences, reduced the activity of the motor system, by blocking the motor simulation of the sentence meaning (E2). This disembodiment effect of negation confirms other results reported in the literature.

6) The effect of negation is strictly bounded to the initial stage of sentences comprehension, during the semantic integration of the negation marker and the verb (E2).

7) Most important, the disembodiment effect of negation in action sentences was entirely suppressed when the inhibitory network activity was disrupted by offline rTMS targeting rIFG (E2).

8) The suppression of the disembodiment effect resulting from disturbing the rIFG is a strong evidence of the causal role of the response inhibition mechanism in the processing of negation. This supports and reinforces the RIN hypothesis (E2).

References:

Abrevaya, S., Sedeño, L., Fitipaldi, S., Pineda, D., Lopera, F., Buritica, O., Villegas, A., Bustamante, C., Gomez, D., Trujillo, N., Pautassi, R., Ibáñez, A., & García, A. M. (2017). The Road Less Traveled: Alternative Pathways for Action-Verb Processing in Parkinson's Disease. *Journal of Alzheimer's Disease*, *55*, 1429–1435. https://doi.org/10.3233/JAD-160737

Alix-Fages, C., Romero-Arenas, S., Castro-Alonso, M., Colomer-Poveda, D., Río-Rodriguez, D., Jerez-Martínez, A., Fernandez-Del-Olmo, M., & Márquez, G. (2019). Short-Term Effects of Anodal Transcranial Direct Current Stimulation on Endurance and Maximal Force Production. A Systematic Review and Meta-Analysis. *Journal of Clinical Medicine*, *8*(4), 536. https://doi.org/10.3390/jcm8040536

Ambrus, G. G., Al-Moyed, H., Chaieb, L., Sarp, L., Antal, A., & Paulus, W. (2012). The fade-in - Short stimulation - Fade out approach to sham tDCS - Reliable at 1 mA for naïve and experienced subjects, but not investigators. *Brain Stimulation*. https://doi.org/10.1016/j.brs.2011.12.001

Ammann, C., Lindquist, M. A., & Celnik, P. A. (2017). Response variability of different anodal transcranial direct current stimulation intensities across multiple sessions. *Brain Stimulation*. https://doi.org/10.1016/j.brs.2017.04.003

Aravena, P., Delevoye-Turrell, Y., Deprez, V., Cheylus, A., Paulignan, Y., Frak, V., & Nazir, T. (2012). Grip Force Reveals the Context Sensitivity of Language-Induced Motor Activity during "Action Words" Processing: Evidence from Sentential Negation. *PLoS ONE*, *7*(12). https://doi.org/10.1371/journal.pone.0050287

Aravena, P., Hurtado, E., Riveros, R., Cardona, J. F., Manes, F., & Ibáñez, A. (2010). Applauding with closed hands: Neural signature of action-sentence compatibility effects. *PLoS ONE*, *5*(7). https://doi.org/10.1371/journal.pone.0011751

Aron, A. R. (2011). From reactive to proactive and selective control: Developing a richer model for stopping inappropriate responses. In *Biological Psychiatry* (Vol. 69, Issue 12, pp. e55–e68). Elsevier. https://doi.org/10.1016/j.biopsych.2010.07.024

Aron, A. R., Behrens, T. E., Smith, S., Frank, M. J., & Poldrack, R. A. (2007). Triangulating a Cognitive Control Network Using Diffusion-Weighted Magnetic Resonance Imaging (MRI) and Functional MRI. *Journal of Neuroscience*, *27*(14), 3743–3752. https://doi.org/10.1523/JNEUROSCI.0519-07.2007

Aron, A. R., Fletcher, P. C., Bullmore, E. T., Sahakian, B. J., & Robbins, T. W. (2003). Stop-signal inhibition disrupted by damage to right inferior frontal gyrus in humans. *Nature Neuroscience*, *6*(2), 115–116. https://doi.org/10.1038/nn1003

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: One decade on. *Trends in Cognitive Sciences*, *18*(4), 177–185. https://doi.org/10.1016/j.tics.2013.12.003

Avenanti, A., Annella, L., Candidi, M., Urgesi, C., & Aglioti, S. M. (2013). Compensatory Plasticity in the Action Observation Network: Virtual Lesions of STS Enhance Anticipatory Simulation of Seen Actions. *Cerebral Cortex*, *23*(3), 570–580. https://doi.org/10.1093/cercor/bhs040

Avenanti, A., Bolognini, N., Maravita, A., & Aglioti, S. M. (2007). Somatic and Motor Components of Action Simulation. *Current Biology*, *17*(24), 2129–2135. https://doi.org/https://doi.org/10.1016/j.cub.2007.11.045

Avenanti, A., Candidi, M., & Urgesi, C. (2013). Vicarious motor activation during action perception: beyond correlational evidence. *Frontiers in Human Neuroscience*, *7*, 185. https://doi.org/10.3389/fnhum.2013.00185

Avenanti, A., Coccia, M., Ladavas, E., Provinciali, L., & Ceravolo, M. G. (2012). Low-frequency rTMS promotes use-dependent motor plasticity in chronic stroke: a randomized trial. *Neurology*, *78*(4), 256–264. https://doi.org/10.1212/WNL.0b013e3182436558

Avenanti, A., Paracampo, R., Annella, L., Tidoni, E., & Aglioti, S. M. (2018). Boosting and decreasing action prediction abilities through excitatory and inhibitory tDCS of inferior frontal cortex. *Cerebral Cortex*, *28*(4), 1282–1296. https://doi.org/10.1093/cercor/bhx041

Aziz-Zadeh, L., Wilson, S. M., Rizzolatti, G., & Iacoboni, M. (2006). Congruent Embodied Representations for Visually Presented Actions and Linguistic Phrases Describing Actions. *Current Biology*, *16*(18), 1818–1823. https://doi.org/10.1016/j.cub.2006.07.060

Bahlmann, J., Mueller, J. L., Makuuchi, M., & Friederici, A. D. (2011). Perisylvian functional connectivity during processing of sentential negation. *Frontiers in Psychology*, *2*(MAY), 1–10. https://doi.org/10.3389/fpsyg.2011.00104

Bari, A., & Robbins, T. W. (2013). Inhibition and impulsivity: Behavioral and neural basis of response control. *Progress in Neurobiology*, *108*, 44–79. https://doi.org/10.1016/j.pneurobio.2013.06.005

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*(4), 577–660. https://doi.org/DOI: undefined

Barsalou, L. W. (2008). Grounded Cognition. *Annual Review of Psychology*, *59*(1), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Barsalou, L. W., Santos, A., Kyle Simmons, W., & Wilson, C. D. (2008). Language and simulation in conceptual processing BT - Symbols and Embodiment: Debates on Meaning and Cognition. In *Symbols and Embodiment: Debates on Meaning and Cognition* (Issue 13, pp. 245–283). https://doi.org/10.10910.1093/acprof:oso/9780199217274.001.0001

Bartoli, E., Tettamanti, A., Farronato, P., Caporizzo, A., Moro, A., Gatti, R., Perani, D., & Tettamanti, M. (2013). The disembodiment effect of negation: negating action-related sentences attenuates their interference on congruent upper limb movements. *Journal of Neurophysiology*. https://doi.org/10.1152/jn.00894.2012

Batsikadze, G., Moliadze, V., Paulus, W., Kuo, M.-F., & Nitsche, M. A. (2013). Partially non-linear stimulation intensity-dependent effects of direct current stimulation on motor cortex excitability in humans. *The Journal of Physiology*, *591*(7), 1987–2000. https://doi.org/10.1113/jphysiol.2012.249730

Beltrán, D., Muñetón-Ayala, M., & de Vega, M. (2018). Sentential negation modulates inhibition in a stop-signal task. Evidence from behavioral and ERP data. *Neuropsychologia*, *112*(February), 10–18. https://doi.org/10.1016/j.neuropsychologia.2018.03.004

Birba, A., García-Cordero, I., Kozono, G., Legaz, A., Ibáñez, A., Sedeño, L., & García, A. M. (2017). Losing ground: Frontostriatal atrophy disrupts language embodiment in Parkinson's and Huntington's disease. *Neuroscience & Biobehavioral Reviews*, *80*, 673–687. https://doi.org/10.1016/J.NEUBIOREV.2017.07.011

Blakemore, S.-J., & Frith, C. (2005). The role of motor contagion in the prediction of action. *Neuropsychologia*, *43*(2), 260–267. https://doi.org/10.1016/j.neuropsychologia.2004.11.012

Bokura, H., Yamaguchi, S., & Kobayashi, S. (2001). Electrophysiological correlates for response inhibition in a Go/NoGo task. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, *112*(12), 2224–2232. https://doi.org/10.1016/s1388-2457(01)00691-5

Borgomaneri, S., Serio, G., & Battaglia, S. (2020). Please, don't do it! Fifteen years of progress of non-invasive brain stimulation in action inhibition. *Cortex*, *132*(September), 404–422.

https://doi.org/10.1016/j.cortex.2020.09.002

Borreggine, K. L., & Kaschak, M. P. (2006). The Action-Sentence Compatibility Effect: It's All in the Timing. In *Cognitive Science* (Vol. 30, Issue 6, pp. 1097–1112). Lawrence Erlbaum. https://doi.org/10.1207/s15516709cog0000_91

Boulenger, V., Roy, A. C., Paulignan, Y., Deprez, V., Jeannerod, M., & Nazir, T. A. (2006). Cross-talk between language processes and overt motor behavior in the first 200 msec of processing. *Journal of Cognitive Neuroscience*, *18*(10), 1607–1615. https://doi.org/10.1162/jocn.2006.18.10.1607

Buccino, G., Binkofski, F., & Riggio, L. (2004). The mirror neuron system and action recognition. *Brain and Language*, *89*(2), 370–376. https://doi.org/10.1016/S0093-934X(03)00356-0

Buccino, G., Riggio, L., Melli, G., Binkofski, F., Gallese, V., & Rizzolatti, G. (2005). Listening to action-related sentences modulates the activity of the motor system: A combined TMS and behavioral study. *Cognitive Brain Research*, *24*(3), 355–363. https://doi.org/10.1016/j.cogbrainres.2005.02.020

Buch, E. R., Santarnecchi, E., Antal, A., Born, J., Celnik, P. A., Classen, J., Gerloff, C., Hallett, M., Hummel, F. C., Nitsche, M. A., Pascual-Leone, A., Paulus, W., Reis, J., Robertson, E. M., Rothwell, J. C., Sandrini, M., Schambra, H. M., Wassermann, E. M., Ziemann, U., & Cohen, L. G. (2017). Effects of tDCS on motor learning and memory formation: A consensus and critical position paper. *Clinical Neurophysiology*, *128*(4), 589–603. https://doi.org/10.1016/J.CLINPH.2017.01.004

Buchwald, A., Calhoun, H., Rimikis, S., Lowe, M. S., Wellner, R., & Edwards, D. J. (2019). Using tDCS to facilitate motor learning in speech production: The role of timing. *Cortex*, *111*, 274–285. https://doi.org/10.1016/j.cortex.2018.11.014

Candidi, M., Leone-Fernandez, B., Barber, H. A., Carreiras, M., & Aglioti, S. M. (2010). Hands on the future: Facilitation of cortico-spinal hand-representation when reading the future tense of hand-related action verbs. *European Journal of Neuroscience*, *32*(4), 677–683. https://doi.org/10.1111/j.1460-9568.2010.07305.x

Cantello, R., Gianelli, M., Civardi, C., & Mutani, R. (1992). Magnetic brain stimulation: the silent period after the motor evoked potential. *Neurology*, *42*(10), 1951–1959. https://doi.org/10.1212/wnl.42.10.1951

Cardona, J. F., Gershanik, O., Gelormini-Lezama, C., Houck, A. L., Cardona, S., Kargieman, L., Trujillo, N., Arévalo, A., Amoruso, L., Manes, F., & Ibáñez, A. (2013). Action-verb processing in Parkinson's disease: new pathways for motor–language coupling. *Brain Structure and Function*, *218*(6), 1355–1373. https://doi.org/10.1007/s00429-013-0510-1

Carpenter, P. A., & Just, M. A. (1975). Sentence comprehension: A psycholinguistic processing model of verification. *Psychological Review*, *82*(1), 45–73. https://doi.org/10.1037/h0076248

Carpenter, P. A., Just, M. a, Keller, T. a, Eddy, W. F., & Thulborn, K. R. (1999). Time course of fMRI-activation in language and spatial networks during sentence comprehension. *NeuroImage*, *10*(2), 216–224. https://doi.org/10.1006/nimg.1999.0465

Chambers, C. D., Bellgrove, M. A., Gould, I. C., English, T., Garavan, H., McNaught, E., Kamke, M., & Mattingley, J. B. (2007). Dissociable Mechanisms of Cognitive Control in Prefrontal and Premotor Cortex. *Journal of Neurophysiology*, *98*(6), 3638–3647. https://doi.org/10.1152/jn.00685.2007

Chambers, C. D., Bellgrove, M. A., Stokes, M. G., Henderson, T. R., Garavan, H., Robertson, I. H., Morris, A. P., & Mattingley, J. B. (2006). Executive "Brake Failure" following Deactivation of Human Frontal Lobe. *Journal of Cognitive Neuroscience*, *18*(3), 444–455. https://doi.org/10.1162/jocn.2006.18.3.444

Chambers, C. D., Garavan, H., & Bellgrove, M. A. (2009). Insights into the neural basis of response inhibition from cognitive and clinical neuroscience. *Neuroscience and Biobehavioral Reviews*, *33*(5), 631–646. https://doi.org/10.1016/j.neubiorev.2008.08.016

Chatterjee, A. (2010). Disembodying cognition. *Language and Cognition*, *2*(1), 79–116. https://doi.org/10.1515/LANGCOG.2010.004

Chen, C. Y., Muggleton, N. G., Tzeng, O. J. L., Hung, D. L., & Juan, C. H. (2009). Control of prepotent responses by the superior medial frontal cortex. *NeuroImage*, *44*(2), 537–545. https://doi.org/10.1016/j.neuroimage.2008.09.005

Chen, R., Classen, J., Gerloff, C., Celnik, P., Wassermann, E. M., Hallett, M., & Cohen, L. G. (1997). Depression of motor cortex excitability by low-frequency transcranial magnetic stimulation. *Neurology*, *48*(5), 1398 LP – 1403. https://doi.org/10.1212/WNL.48.5.1398

Chen, R., Lozano, A. M., & Ashby, P. (1999). Mechanism of the silent period following transcranial magnetic stimulation. Evidence from epidural recordings. *Experimental Brain Research*, *128*(4), 539–542. https://doi.org/10.1007/s002210050878

Chew, T., Ho, K. A., & Loo, C. K. (2015). Inter- and intra-individual variability in response to transcranial direct current stimulation (tDCS) at varying current intensities. *Brain Stimulation*, *8*(6), 1130–1137. https://doi.org/10.1016/j.brs.2015.07.031

Christensen, K. R. (2009). Negative and affirmative sentences increase activation in different areas in the brain. *Journal of Neurolinguistics*, *22*(1), 1–17. https://doi.org/10.1016/j.jneuroling.2008.05.001

Clark, H. H., & Chase, W. G. (1972). On the process of comparing sentences against pictures. *Cognitive Psychology*, *3*(3), 472–517. https://doi.org/10.1016/0010-0285(72)90019-9

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155. https://doi.org/10.1037/0033-2909.112.1.155

Cohen, M. X. (2014). A neural microcircuit for cognitive conflict detection and signaling. *Trends in Neurosciences*, *37*(9), 480–490. https://doi.org/10.1016/j.tins.2014.06.004

Convento, S., Bolognini, N., Fusaro, M., Lollo, F., & Vallar, G. (2014). Neuromodulation of parietal and motor activity affects motor planning and execution. *Cortex*, *57*, 51–59. https://doi.org/10.1016/J.CORTEX.2014.03.006

Dalla Volta, R., Fabbri-Destro, M., Gentilucci, M., & Avanzini, P. (2014). Spatiotemporal dynamics during processing of abstract and concrete verbs: An ERP study. *Neuropsychologia*, *61*(1), 163–174. https://doi.org/10.1016/j.neuropsychologia.2014.06.019

Dalla Volta, R., Gianelli, C., Campione, G. C., & Gentilucci, M. (2009). Action word understanding and overt motor behavior. *Experimental Brain Research*, *196*(3), 403–412. https://doi.org/10.1007/s00221-009-1864-8

Datta, A., Bansal, V., Diaz, J., Patel, J., Reato, D., & Bikson, M. (2009). Gyri-precise head model of transcranial direct current stimulation: improved spatial focality using a ring electrode versus conventional rectangular pad. *Brain Stimulation*, *2*(4), 201-207.e1. https://doi.org/10.1016/j.brs.2009.03.005

de Vega, M. (2015). Toward an embodied approach to inferences in comprehension: the case of action language. In A. E. Cook, E. J. O'Brien, & J. Lorch Robert F. (Eds.), *Inferences during Reading* (pp. 182–209). Cambridge University Press. https://doi.org/DOI: 10.1017/CBO9781107279186.010

de Vega, M., Glenberg, A., & Graesser, A. (2008). *Symbols and Embodiment: Debates on Meaning* *and Cognition*. Oxford University Press.

de Vega, M., León, I., Hernández, J. A., Valdés, M., Padrón, I., & Ferstl, E. C. (2014). Action Sentences Activate Sensory Motor Regions in the Brain Independently of Their Status of Reality. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/jocn_a_00559

de Vega, M., Moreno, I., García-Marco, E., Dutriaux, L., & Gyselinck, V. (n.d.). Crossing hands behind your back reduces recall of manual action sentences and alters motoric EEG rhythms. *Manuscript Submitted for Publication.*

de Vega, M., Moreno, V., & Castillo, D. (2013). The comprehension of action-related sentences may cause interference rather than facilitation on matching actions. *Psychological Research*. https://doi.org/10.1007/s00426-011-0356-1

de Vega, M., Morera, Y., Leon, I., Beltrán, D., Casado, P., & Martin-Loeches, M. (2016). Sentential Negation Might Share Neurophysiological Mechanisms with Action Inhibition. Evidence from Frontal Theta Rhythm. *Journal of Neuroscience*. https://doi.org/10.1523/JNEUROSCI.3736-15.2016

Desai, R. H., Binder, J. R., Conant, L. L., & Seidenberg, M. S. (2010). *Activation of Sensory--Motor Areas in Sentence Comprehension*. *February*. https://doi.org/10.1093/cercor/bhp115

Devanne, H., Lavoie, B. A., & Capaday, C. (1997). Input-output properties and gain changes in the human corticospinal pathway. *Experimental Brain Research*, *114*(2), 329–338. https://doi.org/10.1007/PL00005641

Di Lazzaro, V., Ziemann, U., & Lemon, R. N. (2008). State of the art: Physiology of transcranial motor cortex stimulation. *Brain Stimulation*, *1*(4), 345–362. https://doi.org/10.1016/j.brs.2008.07.004

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica*, *30*, 412–431. https://doi.org/10.1016/0001-6918(69)90065-1

Drewe, E. A. (1975). Go - no go learning after frontal lobe lesions in humans. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *11*(1), 8–16. https://doi.org/10.1016/s0010-9452(75)80015-3

Duchon, A., Perea, M., Sebastián-Gallés, N., Martí, A., & Carreiras, M. (2013). EsPal: One-stop shopping for Spanish word properties. *Behavior Research Methods*, *45*(4), 1246–1258. https://doi.org/10.3758/s13428-013-0326-1

Dutriaux, L., Dahiez, X., & Gyselinck, V. (2018). How to change your memory of an object with a posture and a verb. *Quarterly Journal of Experimental Psychology*. https://doi.org/10.1177/1747021818785096

Dutriaux, L., & Gyselinck, V. (2016). Learning is better with the hands free: The role of posture in the memory of manipulable objects. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0159108

Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Motor facilitation during action observation: a magnetic stimulation study. *Journal of Neurophysiology*, *73*(6), 2608–2611. https://doi.org/10.1152/jn.1995.73.6.2608

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). *G * Power 3 : A flexible statistical power analysis program for the social , behavioral , and biomedical sciences*. *39*(2), 175–191.

Fiori, F., Chiappini, E., & Avenanti, A. (2018). Enhanced action performance following TMS manipulation of associative plasticity in ventral premotor-motor pathway. *NeuroImage*, *183*(September), 847–858. https://doi.org/10.1016/j.neuroimage.2018.09.002

Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *The Quarterly Journal of Experimental Psychology*. https://doi.org/10.1080/17470210701623605

Floden, D., & Stuss, D. T. (2006). Inhibitory Control is Slowed in Patients with Right Superior Medial Frontal Damage. *Journal of Cognitive Neuroscience*, *18*(11), 1843–1849. https://doi.org/10.1162/jocn.2006.18.11.1843

Fodor, J. A. (1975). *The language of thought.* Harvard University Press. Fodor,.

Fodor, J. A. (1983). *The modularity of mind*. Cambridge, MA: Harvard University Press.

Fodor, J. A., & Pylyshyn, Z. W. (2015). Minds without Meanings. In *Minds without Meanings*. https://doi.org/10.7551/mitpress/9780262027908.001.0001

Foroni, F., & Semin, G. R. (2013). Comprehension of action negation involves inhibitory simulation. *Frontiers in Human Neuroscience*, *7*(MAY), 1–7. https://doi.org/10.3389/fnhum.2013.00209

Fritsch, B., Reis, J., Martinowich, K., Schambra, H. M., Ji, Y., Cohen, L. G., & Lu, B. (2010). Direct current stimulation promotes BDNF-dependent synaptic plasticity: Potential implications for motor learning. *Neuron*, *66*(2), 198–204. https://doi.org/10.1016/j.neuron.2010.03.035

Gallese, V. (2007). Before and below “theory of mind”: Embodied simulation and the neural correlates of social cognition. *Philosophical Transactions of the Royal Society B: Biological*

Sciences, *362*(1480), 659–669. https://doi.org/10.1098/rstb.2006.2002

Gallese, V. (2008). Mirror neurons and the social nature of language: the neural exploitation hypothesis. *Social Neuroscience*, *3*(3–4), 317–333. https://doi.org/10.1080/17470910701563608

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain*, *119*(2), 593–609. https://doi.org/10.1093/brain/119.2.593

Gallese, V., & Lakoff, G. (2005). The Brain's concepts: the role of the Sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology*, *22*(3–4), 455–479. https://doi.org/10.1080/02643290442000310

Gandiga, P. C., Hummel, F. C., & Cohen, L. G. (2006). Transcranial DC stimulation (tDCS): A tool for double-blind sham-controlled clinical studies in brain stimulation. *Clinical Neurophysiology*, *117*(4), 845–850. https://doi.org/10.1016/j.clinph.2005.12.003

García-Marco, E., Morera, Y., Beltrán, D., de Vega, M., Herrera, E., Sedeño, L., Ibáñez, A., & García, A. M. (2019). Negation markers inhibit motor routines during typing of manual action verbs. *Cognition*, *182*(June 2018), 286–293. https://doi.org/10.1016/j.cognition.2018.10.020

García, A. M., Abrevaya, S., Kozono, G., Cordero, I. G., Córdoba, M., Kauffman, M. A., Pautassi, R., Muñoz, E., Sedeño, L., & Ibáñez, A. (2017). The cerebellum and embodied semantics: evidence from a case of genetic ataxia due to STUB1 mutations. *Journal of Medical Genetics*, *54*(2), 114–124. https://doi.org/10.1136/jmedgenet-2016-104148

García, A. M., & Ibáñez, A. (2016). A touch with words: Dynamic synergies between manual actions and language. *Neuroscience & Biobehavioral Reviews*, *68*, 59–95. https://doi.org/http://dx.doi.org/10.1016/j.neubiorev.2016.04.022

García, A. M., & Ibáñez, A. (2018). When embodiment breaks down: Language deficits as novel avenues into movement disorders. *Cortex*, *100*, 1–7. https://doi.org/10.1016/J.CORTEX.2017.12.022

García, A. M., Moguilner, S., Torquati, K., García-Marco, E., Herrera, E., Muñoz, E., Castillo, E. M., Kleineschay, T., Sedeño, L., & Ibáñez, A. (2019). How meaning unfolds in neural time: Embodied reactivations can precede multimodal semantic effects during language processing. *NeuroImage*, *197*(November 2018), 439–449. https://doi.org/10.1016/j.neuroimage.2019.05.002

Gerfo, E. Lo, Oliveri, M., Torriero, S., Salerno, S., Koch, G., & Caltagirone, C. (2008). The influence of rTMS over prefrontal and motor areas in a morphological task: Grammatical vs. semantic effects. *Neuropsychologia*. https://doi.org/10.1016/j.neuropsychologia.2007.10.012

Gijssels, T., Ivry, R. B., & Casasanto, D. (2018). tDCS to premotor cortex changes action verb understanding : Complementary effects of inhibitory and excitatory stimulation. *Scientific Reports*, *April*, 4–10. https://doi.org/10.1038/s41598-018-29600-6

Glenberg, A. M. (1997). What memory is for. *The Behavioral and Brain Sciences*, *20*(1), 1–55. https://doi.org/10.1017/s0140525x97000010

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review*, *9*(3), 558–565. https://doi.org/10.3758/BF03196313

Glenberg, A. M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D., & Buccino, G. (2008). Processing abstract language modulates motor system activity. *Quarterly Journal of Experimental Psychology*. https://doi.org/10.1080/17470210701625550

Glenberg, A. M., Witt, J. K., & Metcalfe, J. (2013). From the Revolution to Embodiment: 25 Years of Cognitive Psychology. *Perspectives on Psychological Science*, *8*(5), 573–585. https://doi.org/10.1177/1745691613498098

Goldsworthy, M. R., Müller-Dahlhaus, F., Ridding, M. C., & Ziemann, U. (2015). Resistant Against De-depression: LTD-Like Plasticity in the Human Motor Cortex Induced by Spaced cTBS. *Cerebral Cortex*, *25*(7), 1724–1734. https://doi.org/10.1093/cercor/bht353

Grafton, S. T., Arbib, M. A., Fadiga, L., & Rizzolatti, G. (1996). Localization of grasp representations in humans by positron emission tomography. *Experimental Brain Research*, *112*(1), 103–111. https://doi.org/10.1007/BF00227183

Griffiths, T. L., Steyvers, M., & Firl, A. (2007). Google and the mind: Predicting fluency with pagerank. *Psychological Science*, *18*(12), 1069–1076. https://doi.org/10.1111/j.1467-9280.2007.02027.x

Harnad, S. (1990). The symbol grounding problem. *Physica D: Nonlinear Phenomena*, *42*(1–3), 335–346. https://doi.org/10.1016/0167-2789(90)90087-6

Harper, J., Malone, S. M., & Bernat, E. M. (2014). Theta and delta band activity explain N2 and P3 ERP component activity in a go/no-go task. *Clinical Neurophysiology*, *125*(1), 124–132. https://doi.org/10.1016/j.clinph.2013.06.025

Hashemirad, F., Zoghi, M., Fitzgerald, P. B., & Jaberzadeh, S. (2016). The effect of anodal transcranial direct current stimulation on motor sequence learning in healthy individuals: A systematic review and meta-analysis. *Brain and Cognition*, *102*, 1–12. https://doi.org/10.1016/J.BANDC.2015.11.005

Hauk, O., Shtyrov, Y., & Pulvermüller, F. (2008). The time course of action and action-word comprehension in the human brain as revealed by neurophysiology. *Journal of Physiology Paris*, *102*(1–3), 50–58. https://doi.org/10.1016/j.jphysparis.2008.03.013

Hauk, Olaf, Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic Representation of Action Words in Human Motor and Premotor Cortex. *Neuron*, *41*(2), 301–307. https://doi.org/10.1016/S0896-6273(03)00838-9

Hauk, Olaf, & Pulvermüller, F. (2004). Neurophysiological Distinction of Action Words in the Fronto-Central Cortex. *Human Brain Mapping*, *21*(3), 191–201. https://doi.org/10.1002/hbm.10157

Henson, R. N. A., & Rugg, M. D. (2003). Neural response suppression, haemodynamic repetition effects, and behavioural priming. *Neuropsychologia*, *41*(3), 263–270. https://doi.org/10.1016/s0028-3932(02)00159-8

Herrera, E., & Cuetos, F. (2012). Action naming in Parkinson’s disease patients on/off dopamine. *Neuroscience Letters*, *513*(2), 219—222. https://doi.org/10.1016/j.neulet.2012.02.045

Ho, K.-A., Taylor, J. L., Chew, T., Gálvez, V., Alonzo, A., Bai, S., Dokos, S., & Loo, C. K. (2016). The Effect of Transcranial Direct Current Stimulation (tDCS) Electrode Size and Current Intensity on Motor Cortical Excitability: Evidence From Single and Repeated Sessions. *Brain Stimulation*, *9*(1), 1–7. https://doi.org/10.1016/j.brs.2015.08.003

Hodges, J. R., & Patterson, K. (2007). Semantic dementia: a unique clinicopathological syndrome. *The Lancet. Neurology*, *6*(11), 1004–1014. https://doi.org/10.1016/S1474-4422(07)70266-1

Horn, L. R. (1989). *A natural history of negation.* Chicago: Chicago University Press.

Horn, L. R. (2001). *A natural history of negation. CSLI.*

Huster, R. J., Enriquez-Geppert, S., Lavallee, C. F., Falkenstein, M., & Herrmann, C. S. (2013). Electroencephalography of response inhibition tasks: Functional networks and cognitive contributions. *International Journal of Psychophysiology*, *87*(3), 217–233. https://doi.org/10.1016/j.ijpsycho.2012.08.001

Inghilleri, M., Berardelli, A., Cruccu, G., & Manfredi, M. (1993). Silent period evoked by transcranial stimulation of the human cortex and cervicomedullary junction. *The Journal of Physiology*, *466*, 521–534.

Inghilleri, M., Berardelli, A., Marchetti, P., & Manfredi, M. (1996). Effects of diazepam, baclofen and thiopental on the silent period evoked by transcranial magnetic stimulation in humans. *Experimental Brain Research*, *109*(3), 467–472. https://doi.org/10.1007/BF00229631

Innocenti, A., De Stefani, E., Sestito, M., & Gentilucci, M. (2014). Understanding of action-related and abstract verbs in comparison: A behavioral and TMS study. *Cognitive Processing*, *15*(1), 85–92. https://doi.org/10.1007/s10339-013-0583-z

Jackson, P. L., & Decety, J. (2004). Motor cognition: a new paradigm to study self–other interactions. *Current Opinion in Neurobiology*, *14*(2), 259–263. https://doi.org/10.1016/J.CONB.2004.01.020

Jahanshahi, M., & Rothwell, J. (2000). Transcranial magnetic stimulation studies of cognition: an emerging field. *Experimental Brain Research*, *131*(1), 1–9. https://doi.org/10.1007/s002219900224

Jamil, A., Batsikadze, G., Kuo, H.-I., Labruna, L., Hasan, A., Paulus, W., & Nitsche, M. A. (2017). Systematic evaluation of the impact of stimulation intensity on neuroplastic after-effects induced by transcranial direct current stimulation. *The Journal of Physiology*, *595*(4), 1273–1288. https://doi.org/10.1113/JP272738

Jang, S. H., Ahn, S. H., Byun, W. M., Kim, C. S., Lee, M. Y., & Kwon, Y. H. (2009). The effect of transcranial direct current stimulation on the cortical activation by motor task in the human brain: an fMRI study. *Neuroscience Letters*, *460*(2), 117–120. https://doi.org/10.1016/j.neulet.2009.05.037

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *NeuroImage*, *14*(1 Pt 2), S103-9. https://doi.org/10.1006/nimg.2001.0832

Jirak, D., Menz, M. M., Buccino, G., Borghi, A. M., & Binkofski, F. (2010). Grasping language - A short story on embodiment. *Consciousness and Cognition*. https://doi.org/10.1016/j.concog.2010.06.020

Just, M. A., & Carpenter, P. A. (1971). Comprehension of negation with quantification. *Journal of Verbal Learning and Verbal Behavior*, *10*(3), 244–253. https://doi.org/10.1016/S0022-5371(71)80051-8

Kargieman, L., Herrera, E., Baez, S., García, A. M., Dottori, M., Gelormini, C., Manes, F., Gershanik, O., & Ibáñez, A. (2014). Motor–Language Coupling in Huntington's Disease Families . In *Frontiers in Aging Neuroscience* (Vol. 6, p. 122). https://www.frontiersin.org/article/10.3389/fnagi.2014.00122

Kaschak, M. P., & Borreggine, K. L. (2008). Temporal dynamics of the action-sentence compatibility effect. *Quarterly Journal of Experimental Psychology (2006)*, *61*(6), 883–895. https://doi.org/10.1080/17470210701623852

Kaup, B. (2001). Negation and its impact on the accessibility of text information. *Memory & Cognition*, *29*(7), 960–967. https://doi.org/10.3758/BF03195758

Kaup, B., Lüdtke, J., & Zwaan, R. A. (2006). Processing negated sentences with contradictory predicates: Is a door that is not open mentally closed? *Journal of Pragmatics*, *38*(7), 1033–1050. https://doi.org/10.1016/j.pragma.2005.09.012

Kaup, B., & Zwaan, R. A. (2003). Effects of negation and situational presence on the accessibility of text information. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*(3), 439–446. https://doi.org/10.1037/0278-7393.29.3.439

Kaup, B., Zwaan, R. A., & Lüdtke, J. (2007). The experiential view of language comprehension: How is negation represented? *Higher Level Language Processes in the Brain: Inference and Comprehension Processes*, *November*, 255–288.

Kemmerer, D., Gonzalez, J., Talavage, T., Patterson, S., & Wiley, C. (2008). *Neuroanatomical distribution of five semantic components of verbs : Evidence from fMRI*. *107*, 16–43. https://doi.org/10.1016/j.bandl.2007.09.003

Klepp, A., van Dijk, H., Niccolai, V., Schnitzler, A., & Biermann-Ruben, K. (2019). Action verb processing specifically modulates motor behaviour and sensorimotor neuronal oscillations. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-52426-9

Klepp, A., Weissler, H., Niccolai, V., Terhalle, A., Geisler, H., Schnitzler, A., & Biermann-Ruben, K. (2014). Neuromagnetic hand and foot motor sources recruited during action verb processing. *Brain and Language*, *128*(1), 41–52. https://doi.org/10.1016/j.bandl.2013.12.001

Kuipers, J. R., Van Koningsbruggen, M., & Thierry, G. (2013). Semantic priming in the motor cortex: Evidence from combined repetitive transcranial magnetic stimulation and event-related potential. *NeuroReport*. https://doi.org/10.1097/WNR.0b013e3283631467

Kujirai, T., Caramia, M. D., Rothwell, J. C., Day, B. L., Thompson, P. D., Ferbert, A., Wroe, S., Asselman, P., & Marsden, C. D. (1993). Corticocortical inhibition in human motor cortex. *The Journal of Physiology*, *471*, 501–519. https://doi.org/10.1113/jphysiol.1993.sp019912

Làdavas, E., Giulietti, S., Avenanti, A., Bertini, C., Lorenzini, E., Quinquinio, C., & Serino, A. (2015). a-tDCS on the ipsilesional parietal cortex boosts the effects of prism adaptation treatment in neglect. *Restorative Neurology and Neuroscience*, *33*(5), 647—662. https://doi.org/10.3233/rnn-140464

Lambon Ralph, M. A. (2014). Neurocognitive insights on conceptual knowledge and its breakdown. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634). https://doi.org/10.1098/rstb.2012.0392

Leshinskaya, A., & Caramazza, A. (2016). For a cognitive neuroscience of concepts: Moving beyond the grounding issue. *Psychonomic Bulletin & Review*, *23*(4), 991–1001. https://doi.org/10.3758/s13423-015-0870-z

Liu, B., Gu, B., Beltrán, D., Wang, H., & de Vega, M. (2020). Presetting an inhibitory state modifies the neural processing of negated action sentences. An ERP study. *Brain and Cognition*, *143*(February), 105598. https://doi.org/10.1016/j.bandc.2020.105598

Liuzza, M. T., Candidi, M., & Aglioti, S. M. (2011). Do not resonate with actions: Sentence polarity modulates cortico-spinal excitability during action-related sentence reading. *PLoS ONE*, *6*(2), 38–41. https://doi.org/10.1371/journal.pone.0016855

Liuzzi, G., Freundlieb, N., Ridder, V., Hoppe, J., Heise, K., Zimerman, M., Dobel, C., Enriquez-Geppert, S., Gerloff, C., Zwitserlood, P., & Hummel, F. C. (2010). The involvement of the left motor cortex in learning of a novel action word lexicon. *Current Biology*. https://doi.org/10.1016/j.cub.2010.08.034

Logan, G. D. (1994). *On the ability to inhibit thought and action: A users' guide to the stop signal paradigm* (pp. 189–239). Academic Press.

Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: a model and a method. *Journal of Experimental Psychology. Human Perception and Performance*, *10*(2), 276–291. https://doi.org/10.1037//0096-1523.10.2.276

Loo, C. K., Alonzo, A., Martin, D., Mitchell, P. B., Galvez, V., & Sachdev, P. (2012). Transcranial direct current stimulation for depression: 3-week, randomised, sham-controlled trial. *British Journal of Psychiatry*, *200*(01), 52–59. https://doi.org/10.1192/bjp.bp.111.097634

Loo, C. K., Sachdev, P., Martin, D., Pigot, M., Alonzo, A., Malhi, G. S., Lagopoulos, J., & Mitchell, P. (2010). A double-blind, sham-controlled trial of transcranial direct current stimulation for the treatment of depression. *International Journal of Neuropsychopharmacology*. https://doi.org/10.1017/S1461145709990411

López-Alonso, V., Cheeran, B., & Fernández-Del-Olmo, M. (2015). Relationship between non-invasive brain stimulation-induced plasticity and capacity for motor learning. *Brain Stimulation*. https://doi.org/10.1016/j.brs.2015.07.042

López-Alonso, V., Cheeran, B., Río-Rodríguez, D., & Fernández-Del-Olmo, M. (2014). Inter-individual variability in response to non-invasive brain stimulation paradigms. *Brain Stimulation*, *7*(3), 372–380. https://doi.org/10.1016/j.brs.2014.02.004

MacDonald, M. C., & Just, M. A. (1989). Changes in Activation Levels With Negation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(4), 633–642. https://doi.org/10.1037/0278-7393.15.4.633

Maguire, M. J., Brier, M. R., Moore, P. S., Ferree, T. C., Ray, D., Mostofsky, S., Hart, J. J., & Kraut, M. A. (2009). The influence of perceptual and semantic categorization on inhibitory processing as measured by the N2-P3 response. *Brain and Cognition*, *71*(3), 196–203. https://doi.org/10.1016/j.bandc.2009.08.018

Mahon, B. Z. (2015). What is embodied about cognition? *Language, Cognition and Neuroscience*. https://doi.org/10.1080/23273798.2014.987791

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology Paris*. https://doi.org/10.1016/j.jphysparis.2008.03.004

McDonnell, M. N., Orekhov, Y., & Ziemann, U. (2006). The role of GABA(B) receptors in intracortical inhibition in the human motor cortex. *Experimental Brain Research*, *173*(1), 86–93. https://doi.org/10.1007/s00221-006-0365-2

Meister, I. G., Boroojerdi, B., Foltys, H., Sparing, R., Huber, W., & Töpper, R. (2003). Motor cortex hand area and speech: implications for the development of language. *Neuropsychologia*, *41*(4), 401–406. https://doi.org/10.1016/s0028-3932(02)00179-3

Melloni, M., Sedeño, L., Hesse, E., García-Cordero, I., Mikulan, E., Plastino, A., Marcotti, A., López, J. D., Bustamante, C., Lopera, F., Pineda, D., García, A. M., Manes, F., Trujillo, N., & Ibáñez, A. (2015). Cortical dynamics and subcortical signatures of motor-language coupling in

Parkinson's disease. *Scientific Reports*, *5*, 11899. https://doi.org/10.1038/srep11899

Mollo, G., Pulvermüller, F., & Hauk, O. (2016). Movement priming of EEG/MEG brain responses for action-words characterizes the link between language and action. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *74*, 262–276. https://doi.org/10.1016/j.cortex.2015.10.021

Moreno, I., De Vega, M., & León, I. (2013). Understanding action language modulates oscillatory mu and beta rhythms in the same way as observing actions. *Brain and Cognition*. https://doi.org/10.1016/j.bandc.2013.04.010

Moreno, I., de Vega, M., León, I., Bastiaansen, M., Glen Lewis, A., & Magyari, L. (2015). Brain dynamics in the comprehension of action-related language. A time-frequency analysis of mu rhythms. *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2015.01.018

Mostofsky, S. H., & Simmonds, D. J. (2008). Response inhibition and response selection: Two sides of the same coin. *Journal of Cognitive Neuroscience*, *20*(5), 751–761. https://doi.org/10.1162/jocn.2008.20500

Münchau, A., Bloem, B. R., Irlbacher, K., Trimble, M. R., & Rothwell, J. C. (2002). Functional connectivity of human premotor and motor cortex explored with repetitive transcranial magnetic stimulation. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *22*(2), 554–561. https://doi.org/10.1523/JNEUROSCI.22-02-00554.2002

Nakata, H., Sakamoto, K., Ferretti, A., Gianni Perrucci, M., Del Gratta, C., Kakigi, R., & Luca Romani, G. (2008). Somato-motor inhibitory processing in humans: An event-related functional MRI study. *NeuroImage*, *39*(4), 1858–1866. https://doi.org/10.1016/j.neuroimage.2007.10.041

Neubert, F.-X., Mars, R. B., Buch, E. R., Olivier, E., & Rushworth, M. F. S. (2010). Cortical and subcortical interactions during action reprogramming and their related white matter pathways. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(30), 13240–13245. https://doi.org/10.1073/pnas.1000674107

Niccolai, V., Klepp, A., Indefrey, P., Schnitzler, A., & Biermann-, K. (2017). Semantic discrimination impacts tDCS modulation of verb processing. *Scientific Reports*, 1–11. https://doi.org/10.1038/s41598-017-17326-w

Nigbur, R., Ivanova, G., & Stürmer, B. (2011). Theta power as a marker for cognitive interference. *Clinical Neurophysiology*, *122*(11), 2185–2194. https://doi.org/10.1016/j.clinph.2011.03.030

Nitsche, M. A., Nitsche, M. S., Klein, C. C., Tergau, F., Rothwell, J. C., & Paulus, W. (2003). Level of action of cathodal DC polarisation induced inhibition of the human motor cortex. *Clinical Neurophysiology*, *114*(4), 600–604. https://doi.org/10.1016/S1388-2457(02)00412-1

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, *527 Pt 3*, 633–639. https://doi.org/PHY_1055 [pii]

Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, *57*(10), 1899–1901. https://doi.org/10.1212/WNL.57.10.1899

Nitsche, M. A., Schauenburg, A., Lang, N., Liebetanz, D., Exner, C., Paulus, W., & Tergau, F. (2003). Facilitation of implicit motor learning by weak transcranial direct current stimulation of the primary motor cortex in the human. *Journal Of Cognitive Neuroscience*, *15*(4), 619–626.

Nyffeler, T., Wurtz, P., Lüscher, H.-R., Hess, C. W., Senn, W., Pflugshaupt, T., von Wartburg, R., Lüthi, M., & Müri, R. M. (2006). Extending lifetime of plastic changes in the human brain. *The European Journal of Neuroscience*, *24*(10), 2961–2966. https://doi.org/10.1111/j.1460-9568.2006.05154.x

O'Connell, N. E., Cossar, J., Marston, L., Wand, B. M., Bunce, D., Moseley, G. L., & de Souza, L. H. (2012). Rethinking Clinical Trials of Transcranial Direct Current Stimulation: Participant and Assessor Blinding Is Inadequate at Intensities of 2mA. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0047514

Obeso, I., Wilkinson, L., Teo, J. T., Talelli, P., Rothwell, J. C., & Jahanshahi, M. (2017). Theta burst magnetic stimulation over the pre-supplementary motor area improves motor inhibition. *Brain Stimulation*, *10*(5), 944–951. https://doi.org/10.1016/j.brs.2017.05.008

Oliveri, M., Finocchiaro, C., Shapiro, K., Gangitano, M., Caramazza, A., & Pascual-Leone, A. (2004). All talk and no action: A transcranial magnetic stimulation study of motor cortex activation during action word production. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/089892904322926719

Opitz, A., Paulus, W., Will, S., Antunes, A., & Thielscher, A. (2015). Determinants of the electric field during transcranial direct current stimulation. *NeuroImage*, *109*, 140–150. https://doi.org/10.1016/j.neuroimage.2015.01.033

Orban de Xivry, J.-J., & Shadmehr, R. (2014). Electrifying the motor engram: effects of tDCS on motor learning and control. *Experimental Brain Research*, *232*(11), 3379–3395. https://doi.org/10.1007/s00221-014-4087-6

Page, L., Brin, S., Motwani, R., & Winograd, T. (1999). The PageRank Citation Ranking: Bringing Order to the Web. *Technical Report. Stanford InfoLab.*, 111–112. https://doi.org/10.1109/IISWC.2012.6402911

Papeo, L., Hochmann, J.-R., & Battelli, L. (2016). The Default Computation of Negated Meanings. *Journal of Cognitive Neuroscience*, *28*(12), 1980–1986. https://doi.org/10.1162/jocn_a_01016

Papeo, L., Lingnau, A., Agosta, S., Pascual-Leone, A., Battelli, L., & Caramazza, A. (2015). The origin of word-related motor activity. *Cerebral Cortex (New York, N.Y. : 1991)*, *25*(6), 1668–1675. https://doi.org/10.1093/cercor/bht423

Papeo, L., Pascual-Leone, A., & Caramazza, A. (2013). Disrupting the brain to validate hypotheses on the neurobiology of language. *Frontiers in Human Neuroscience*, *7*, 148. https://doi.org/10.3389/fnhum.2013.00148

Papeo, L., Vallesi, A., Isaja, A., & Rumiati, R. I. (2009). Effects of TMS on different stages of motor and non-motor verb processing in the primary motor cortex. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0004508

Paracampo, R., Montemurro, M., de Vega, M., & Avenanti, A. (2018). Primary motor cortex crucial for action prediction: A tDCS study. *Cortex*. https://doi.org/10.1016/j.cortex.2018.09.019

Pascual-Leone, A., Bartres-Faz, D., & Keenan, J. P. (1999). Transcranial magnetic stimulation: studying the brain-behaviour relationship by induction of “virtual lesions”. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *354*(1387), 1229–1238. https://doi.org/10.1098/rstb.1999.0476

Pascual-Leone, A., Walsh, V., & Rothwell, J. (2000). Transcranial magnetic stimulation in cognitive neuroscience--virtual lesion, chronometry, and functional connectivity. *Current Opinion in Neurobiology*, *10*(2), 232–237. https://doi.org/10.1016/s0959-4388(00)00081-7

Peelen, M. V, Romagno, D., & Caramazza, A. (2012). Independent Representations of Verbs and Actions in Left Lateral Temporal Cortex. *Journal of Cognitive Neuroscience*, *24*(10), 2096–2107. https://doi.org/10.1162/jocn_a_00257

Pobric, G., Jefferies, E., & Lambon Ralph, M. A. (2007). Anterior temporal lobes mediate semantic representation: Mimicking semantic dementia by using rTMS in normal participants.

Proceedings of the National Academy of Sciences of the United States of America, *104*(50), 20137–20141. https://doi.org/10.1073/pnas.0707383104

Pobric, G., Jefferies, E., & Lambon Ralph, M. A. (2010). Amodal semantic representations depend on both anterior temporal lobes: Evidence from repetitive transcranial magnetic stimulation. *Neuropsychologia*, *48*(5), 1336–1342. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2009.12.036

Polanía, R., Nitsche, M. A., & Paulus, W. (2011). Modulating functional connectivity patterns and topological functional organization of the human brain with transcranial direct current stimulation. *Human Brain Mapping*, *32*(8), 1236–1249. https://doi.org/10.1002/hbm.21104

Polanía, R., Nitsche, M. A., & Ruff, C. C. (2018). Studying and modifying brain function with non-invasive brain stimulation. *Nature Neuroscience*, *21*(2), 174–187. https://doi.org/10.1038/s41593-017-0054-4

Polanía, R., Paulus, W., Antal, A., & Nitsche, M. A. (2011). Introducing graph theory to track for neuroplastic alterations in the resting human brain: a transcranial direct current stimulation study. *NeuroImage*, *54*(3), 2287–2296. https://doi.org/10.1016/j.neuroimage.2010.09.085

Pulvermüller, F. (2003). *Spatiotemporal dynamics of neural language processing : an MEG study using minimum-norm current estimates*. *20*, 1020–1025. https://doi.org/10.1016/S1053-8119(03)00356-2

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews. Neuroscience*, *6*(7), 576–582. https://doi.org/10.1038/nrn1706

Pulvermüller, F., Härle, M., & Hummel, F. (2001). Walking or talking?: Behavioral and neurophysiological correlates of action verb processing. *Brain and Language*, *78*(2), 143–168. https://doi.org/10.1006/brln.2000.2390

Pulvermüller, F., Hauk, O., Nikulin, V., & Ilmoniemi, R. (2005). Functional links between motor and language systems. *European Journal of Neuroscience*, *21*(3), 793–797. https://doi.org/10.1111/j.1460-9568.2005.03900.x

Pulvermüller, F., Shtyrov, Y., & Ilmoniemi, R. (2005). Brain signatures of meaning access in action word recognition. *Journal of Cognitive Neuroscience*, *17*(6), 884–892. https://doi.org/10.1162/0898929054021111

Pylyshyn, Z. W. (1984). *Computation and Cognition. Toward a Foundation for Cognitive Science*.

Cambridge, Mass.: MIT Press.

Raposo, A., Moss, H. E., Stamatakis, E. A., & Tyler, L. K. (2009). Modulation of motor and premotor cortices by actions, action words and action sentences. *Neuropsychologia*, *47*(2), 388–396. https://doi.org/10.1016/j.neuropsychologia.2008.09.017

Reis, J., & Fritsch, B. (2011). Modulation of motor performance and motor learning by transcranial direct current stimulation. In *Current Opinion in Neurology*. https://doi.org/10.1097/WCO.0b013e32834c3db0

Reis, J., Swayne, O. B., Vandermeeren, Y., Camus, M., Dimyan, M. A., Harris-Love, M., Perez, M. A., Ragert, P., Rothwell, J. C., & Cohen, L. G. (2008). Contribution of transcranial magnetic stimulation to the understanding of cortical mechanisms involved in motor control. *The Journal of Physiology*, *586*(2), 325–351. https://doi.org/10.1113/jphysiol.2007.144824

Repetto, C., Colombo, B., Cipresso, P., & Riva, G. (2013). The effects of rTMS over the primary motor cortex: The link between action and language. *Neuropsychologia*. https://doi.org/10.1016/j.neuropsychologia.2012.11.001

Rizzolatti, G., & Arbib, M. A. (1998). Language within our grasp. *Trends in Neurosciences*, *21*(5), 188–194. https://doi.org/10.1016/S0166-2236(98)01260-0

Rizzolatti, G., & Craighero, L. (2004). The Mirror-Neuron System. *Annual Review of Neuroscience*, *27*, 169–192. https://doi.org/10.1146/annurev.neuro.27.070203.144230

Rizzolatti, G., & Craighero, L. (2007). Language and mirror neurons. *The Oxford Handbook of Psycholinguistics*, *August 2018*, 1–24. https://doi.org/10.1093/oxfordhb/9780198568971.013.0047

Rizzolatti, G., Fadiga, L., Matelli, M., Bettinardi, V., Paulesu, E., Perani, D., & Fazio, F. (1996). Localization of grasp representations in humans by PET: 1. Observation versus execution. *Experimental Brain Research*, *111*(2), 246–252. https://doi.org/10.1007/BF00227301

Rossini, P. M., Burke, D., Chen, R., Cohen, L. G., Daskalakis, Z., Di Iorio, R., Di Lazzaro, V., Ferreri, F., Fitzgerald, P. B., George, M. S., Hallett, M., Lefaucheur, J. P., Langguth, B., Matsumoto, H., Miniussi, C., Nitsche, M. A., Pascual-Leone, A., Paulus, W., Rossi, S., … Ziemann, U. (2015). Non-invasive electrical and magnetic stimulation of the brain, spinal cord, roots and peripheral nerves: Basic principles and procedures for routine clinical and research application: An updated report from an I.F.C.N. Committee. *Clinical Neurophysiology*, *126*(6), 1071–1107. https://doi.org/10.1016/j.clinph.2015.02.001

Santana, E. J., & Vega, M. De. (2013). An ERP study of motor compatibility effects in action language. *Brain Research*, *1526*, 71–83. https://doi.org/10.1016/j.brainres.2013.06.020

Sato, M., Mengarelli, M., Riggio, L., Gallese, V., & Buccino, G. (2008). Task related modulation of the motor system during language processing. *Brain and Language*, *105*(2), 83–90. https://doi.org/10.1016/j.bandl.2007.10.001

Schütz-Bosbach, S., Avenanti, A., Aglioti, S. M., & Haggard, P. (2009). Don't Do It! Cortical Inhibition and Self-attribution during Action Observation. *Journal of Cognitive Neuroscience*, *21*(6), 1215–1227. https://doi.org/10.1162/jocn.2009.21068

Scorolli, C., Jacquet, P. O., Binkofski, F., Nicoletti, R., Tessari, A., & Borghi, A. M. (2012). Abstract and concrete phrases processing differentially modulates cortico-spinal excitability [Elsevier]. In *Brain Research* (Vol. 1488). https://doi.org/10.1016/j.brainres.2012.10.004

Searle, J. R. (1980). Minds, brains, and programs. *Behavioral and Brain Sciences*, *3*(3), 417–424. https://doi.org/10.1017/S0140525X00005756

Serino, A., Canzoneri, E., & Avenanti, A. (2011). Fronto-parietal areas necessary for a multisensory representation of peripersonal space in humans: an rTMS study. *Journal of Cognitive Neuroscience*, *23*(10), 2956–2967. https://doi.org/10.1162/jocn_a_00006

Sha, G. (2010). Using Google as a super corpus to drive written language learning: a comparison with the British National Corpus. *Computer Assisted Language Learning*, *23*(5), 377–393. https://doi.org/10.1080/09588221.2010.514576

Silvanto, J., & Pascual-Leone, A. (2012). Why the assessment of causality in brain-behavior relations requires brain stimulation. *Journal of Cognitive Neuroscience*, *24*(4), 775–777. https://doi.org/10.1162/jocn_a_00193

Smith, J. L., Johnstone, S. J., & Barry, R. J. (2008). Movement-related potentials in the Go/NoGo task: The P3 reflects both cognitive and motor inhibition. *Clinical Neurophysiology*, *119*(3), 704–714. https://doi.org/10.1016/j.clinph.2007.11.042

Stagg, C. J., Antal, A., & Nitsche, M. A. (2018). Physiology of Transcranial Direct Current Stimulation. In *Journal of ECT*. https://doi.org/10.1097/YCT.0000000000000510

Stagg, C. J., & Nitsche, M. A. (2011). Physiological Basis of Transcranial Direct Current Stimulation. *The Neuroscientist*, *17*(1), 37–53. https://doi.org/10.1177/1073858410386614

Stagg, C. J., O'Shea, J., Kincses, Z. T., Woolrich, M., Matthews, P. M., & Johansen-Berg, H. (2009).

Modulation of movement-associated cortical activation by transcranial direct current stimulation. *The European Journal of Neuroscience*, *30*(7), 1412–1423. https://doi.org/10.1111/j.1460-9568.2009.06937.x

Strube, W., Bunse, T., Malchow, B., & Hasan, A. (2015). Efficacy and interindividual variability in motor-cortex plasticity following anodal tDCS and paired-associative stimulation. *Neural Plasticity*, *2015*, 1–5. https://doi.org/10.1155/2015/530423

Swann, N. C., Cai, W., Conner, C. R., Pieters, T. A., Claffey, M. P., George, J. S., Aron, A. R., & Tandon, N. (2012). Roles for the pre-supplementary motor area and the right inferior frontal gyrus in stopping action: Electrophysiological responses and functional and structural connectivity. *NeuroImage*, *59*(3), 2860–2870. https://doi.org/10.1016/j.neuroimage.2011.09.049

Taylor, L. J., & Zwaan, R. A. (2008). Motor resonance and linguistic focus. *Quarterly Journal of Experimental Psychology*, *61*(6), 896–904. https://doi.org/10.1080/17470210701625519

Terranova, C., Rizzo, V., Cacciola, A., Chillemi, G., Calamuneri, A., Milardi, D., & Quartarone, A. (2019). Is There a Future for Non-invasive Brain Stimulation as a Therapeutic Tool? *Frontiers in Neurology*, *9*, 1146. https://doi.org/10.3389/fneur.2018.01146

Tettamanti, M., Buccino, G., Saccuman, M. C., Gallese, V., Danna, M., Scifo, P., Fazio, F., Rizzolatti, G., Cappa, S. F., & Perani, D. (2005). Listening to Action-related Sentences Activates Fronto-parietal Motor Circuits. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/0898929053124965

Tettamanti, M., Manenti, R., Della Rosa, P. A., Falini, A., Perani, D., Cappa, S. F., & Moro, A. (2008). Negation in the brain: Modulating action representations. *NeuroImage*, *43*(2), 358–367. https://doi.org/10.1016/j.neuroimage.2008.08.004

Tokimura, H., Tokimura, Y., Oliviero, A., Asakura, T., & Rothwell, J. C. (1996). Speech-induced changes in corticospinal excitability. *Annals of Neurology*, *40*(4), 628–634. https://doi.org/10.1002/ana.410400413

Tomasino, B., Fink, G. R., Sparing, R., Dafotakis, M., & Weiss, P. H. (2008). Action verbs and the primary motor cortex: A comparative TMS study of silent reading, frequency judgments, and motor imagery. *Neuropsychologia*, *46*(7), 1915–1926. https://doi.org/10.1016/j.neuropsychologia.2008.01.015

Tomasino, B., Weiss, P. H., & Fink, G. R. (2010). To move or not to move: Imperatives modulate action-related verb processing in the motor system. *Neuroscience*, *169*(1), 246–258. https://doi.org/10.1016/j.neuroscience.2010.04.039

Toni, I., de Lange, F. P., Noordzij, M. L., & Hagoort, P. (2008). Language beyond action. *Journal of Physiology Paris*, *102*(1–3), 71–79. https://doi.org/10.1016/j.jphysparis.2008.03.005

Urgesi, C., Maieron, M., Avenanti, A., Tidoni, E., Fabbro, F., & Aglioti, S. M. (2010). Simulating the future of actions in the human corticospinal system. In *Cerebral Cortex* (Vol. 20, Issue 11, pp. 2511–2521). Oxford University Press. https://doi.org/10.1093/cercor/bhp292

Urgesi, C., Moro, V., Candidi, M., & Aglioti, S. M. (2006). Mapping Implied Body Actions in the Human Motor System. *The Journal of Neuroscience*, *26*(30), 7942 LP – 7949. https://doi.org/10.1523/JNEUROSCI.1289-06.2006

Valchev, N., Ćurčić-Blake, B., Renken, R. J., Avenanti, A., Keysers, C., Gazzola, V., & Maurits, N. M. (2015). cTBS delivered to the left somatosensory cortex changes its functional connectivity during rest. *NeuroImage*, *114*, 386–397. https://doi.org/10.1016/j.neuroimage.2015.04.017

Valchev, N., Gazzola, V., Avenanti, A., & Keysers, C. (2016). Primary somatosensory contribution to action observation brain activity-combining fMRI and cTBS. *Social Cognitive and Affective Neuroscience*, *11*(8), 1205–1217. https://doi.org/10.1093/scan/nsw029

van Dam, W. O., Rueschemeyer, S. A., & Bekkering, H. (2010). How specifically are action verbs represented in the neural motor system: An fMRI study. *NeuroImage*, *53*(4), 1318–1325. https://doi.org/10.1016/j.neuroimage.2010.06.071

van Elk, M., van Schie, H. T., Zwaan, R. A., & Bekkering, H. (2010). The functional role of motor activation in language processing: Motor cortical oscillations support lexical-semantic retrieval. *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2009.12.123

Verbruggen, F., Aron, A. R., Stevens, M. A., & Chambers, C. D. (2010). Theta burst stimulation dissociates attention and action updating in human inferior frontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(31), 13966–13971. https://doi.org/10.1073/pnas.1001957107

Verbruggen, F., & Logan, G. D. (2009). Models of response inhibition in the stop-signal and stop-change paradigms. *Neuroscience and Biobehavioral Reviews*, *33*(5), 647–661. https://doi.org/10.1016/j.neubiorev.2008.08.014

Vitale, F., Padrón, I., Avenanti, A., & de Vega, M. (2021). Enhancing Motor Brain Activity Improves

Memory for Action Language: A tDCS Study. *Cerebral Cortex (New York, N.Y. : 1991)*, *31*(3), 1569–1581. https://doi.org/10.1093/cercor/bhaa309

Vukovic, N., Feurra, M., Shpektor, A., Myachykov, A., & Shtyrov, Y. (2017). Primary motor cortex functionally contributes to language comprehension: An online rTMS study. *Neuropsychologia*. https://doi.org/10.1016/j.neuropsychologia.2017.01.025

Walsh, V., & Rushworth, M. (1999). A primer of magnetic stimulation as a tool for neuropsychology. *Neuropsychologia*, *37*(2), 125–135.

Wiethoff, S., Hamada, M., & Rothwell, J. C. (2014). Variability in response to transcranial direct current stimulation of the motor cortex. *Brain Stimulation*, *7*(3), 468–475. https://doi.org/10.1016/j.brs.2014.02.003

Wilke, S., Groenveld, D., Grittner, U., List, J., & Flöel, A. (2016). cSPider - Evaluation of a free and open-source automated tool to analyze corticomotor silent period. *PLoS ONE*, *11*(6), 1–15. https://doi.org/10.1371/journal.pone.0156066

Willems, R. M., Labruna, L., D'Esposito, M., Ivry, R., & Casasanto, D. (2011). A Functional Role for The Motor System in Language Understanding: Evidence from Theta-Burst Transcranial Magnetic Stimulation. *Psychological Science*. https://doi.org/10.1177/0956797611412387

Willems, R. M., Toni, I., Hagoort, P., & Casasanto, D. (2010). Neural dissociations between action verb understanding and motor imagery. *Journal of Cognitive Neuroscience*, *22*(10), 2387–2400. https://doi.org/10.1162/jocn.2009.21386

Wilson, M., & Knoblich, G. (2005). The Case for Motor Involvement in Perceiving Conspecifics. In *Psychological Bulletin* (Vol. 131, Issue 3, pp. 460–473). American Psychological Association. https://doi.org/10.1037/0033-2909.131.3.460

Wolpert, D. M., Doya, K., & Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *358*(1431), 593–602. https://doi.org/10.1098/rstb.2002.1238

Zanon, M., Borgomaneri, S., & Avenanti, A. (2018). Action-related dynamic changes in inferior frontal cortex effective connectivity: A TMS/EEG coregistration study. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *108*, 193–209. https://doi.org/10.1016/j.cortex.2018.08.004

Zhang, R., Geng, X., & Lee, T. M. C. (2017). Large-scale functional neural network correlates of response inhibition: an fMRI meta-analysis. *Brain Structure and Function*, *222*(9), 3973–3990. https://doi.org/10.1007/s00429-017-1443-x

Ziemann, U., Rothwell, J. C., & Ridding, M. C. (1996). Interaction between intracortical inhibition and facilitation in human motor cortex. *The Journal of Physiology*, *496 (Pt 3*(Pt 3), 873–881. https://doi.org/10.1113/jphysiol.1996.sp021734

Zwaan, R. A., & Taylor, L. J. (2006). Seeing, Acting, Understanding: Motor Resonance in Language Comprehension. *Journal of Experimental Psychology: General*. https://doi.org/10.1037/0096-3445.135.1.1

Appendix

Appendix 1: List of verbs and the correspondent linguistic variables used in the first and second study

MANUAL ACTION VERBS	Frequency	Length	Familiarity	Concreteness
Abrir / *to open*	49,075	5	6,800	6,429
Agarrar / *to hold*	4,692	7	6,600	6,357
Agitar / *to shake*	1,456	6	5,867	5,429
Apagar / *to turn off*	4,598	6	6,700	6,500
Apretar / *to tighten*	2,843	7	6,167	6,143
Coger / *to take*	11,271	5	6,520	5,889
Colgar / *to hang*	2,798	6	5,967	5,857
Colocar / *to place*	17,441	7	6,433	5,714
Dar / *to give*	301,281	3	6,733	5,429
Depositar / *to deposit (put)*	3,395	9	5,200	5,571
Doblar / *to fold*	4,000	6	6,133	6,143
Empujar / *to push*	2,940	7	6,200	6,071
Encender / *to turn on* / *to light*	5,309	8	6,533	5,429
Enjuagar / *to dry*	0,107	8	5,467	6,071
Guardar / *to put away*	17,259	7	6,733	5,429
Levantar / *to raise*	22,913	8	6,700	6,143
Limpiar / *to clean*	7,350	7	6,833	6,357
Llenar / *to fill*	11,814	6	6,733	6,000
Manejar / *to handle*	12,902	7	5,800	5,500
Manipular / *to manipulate*	4,916	9	5,367	4,929
Mover / *to move*	16,275	5	6,900	5,714
Ponerse / *to put on*	25,054	7	6,167	5,000
Recoger / *to pick up*	21,610	7	6,400	5,714
Registrar / *to search*	8,110	9	5,200	4,786
Retirar / *to remove*	19,540	7	5,233	4,429
Sacar / *to take out*	46,840	5	6,300	5,429
Sujetar / *to grab*	2,502	7	5,967	6,071
Tirar / *to throw*	11,327	5	6,667	6,000
Utilizar / *to use*	73,502	8	6,400	5,286
Vaciar / *to empty*	1,826	6	6,333	5,857

ATTENTIONAL VERBS	Frequency	Length	Familiarity	Concreteness
Admirar / *to admire*	6,641	7	5,767	4,071
Adorar / *to adore*	2,382	6	5,100	3,929
Apreciar / *to appreciate*	18,046	8	5,567	3,500
Conocer / *to know*	104,155	7	6,533	3,786
Contemplar / *to contemplate*	16,074	10	5,200	4,429
Desear / *to desire*	22,071	6	6,367	3,643
Despreciar / *to despise*	2,339	10	5,000	3,714
Distinguir / *to distinguish*	21,513	10	5,433	4,143
Divisar / *to spot*	1,738	7	3,967	3,857
Encontrar / *to find*	131,860	9	6,467	5,571
Extraviar / *to mislay*	0,240	9	4,500	4,357
Gustar / *to like*	66,621	6	6,600	4,071
Imaginar / *to imagine*	16,106	8	6,267	3,357
Mirar / *to look at*	39,952	5	6,867	5,571
Necesitar / *to need*	8,025	9	6,467	3,786
Observar / *to observe*	40,293	8	6,233	5,286
Oír / *to listen to*	75,702	3	6,733	5,000
Olvidar / *to forget*	34,698	7	6,300	4,071
Pedir / *to ask for*	64,142	5	6,367	5,214
Percibir / *to perceive*	12,551	8	5,233	3,500
Perder / *to lose*	65,597	6	6,500	4,714
Preferir / *to prefer*	4,367	8	6,033	4,286
Querer / *to want*	31,708	6	6,867	3,857
Rechazar / *to reject*	17,971	8	5,700	3,714
Reclamar / *to demand*	11,333	8	5,333	4,429
Reconocer / *to recognize*	49,446	9	6,033	4,214
Recordar / *to remember*	58,563	8	6,733	4,500
Solicitar / *to request*	17,984	9	5,300	3,714
Tener / *to have*	368,360	5	6,767	5,000
Ver / *to see*	394,697	3	6,967	5,000

Appendix 2: Sets of sentences and the co-occurrence values used in the first study

Set 1:

ACTION SENTENCES	Co-occurence
Abrir un cuaderno / *to open a notebook*	74100
Abrir un paraguas / *to open an umbrella*	50200
Agarrar un cascanueces / *to hold a nutcracker*	1
Agarrar la tenaza / *to hold the pliers*	823
Agitar una coctelera / *to shake a shaker*	882
Agitar una castañuela / *to shake a castanet*	0
Apagar un video / *to turn off a video*	34400
Apagar un micrófono / *to turn off a microphone*	3920
Apretar un tornillo / *to tighten a screw*	32400
Apretar un nudo / *to tighten a knot*	8980
Coger una regla / *to take a ruler*	28800
Coger una cafetera / *to take a coffee maker*	6200
Colgar un colador / *to hang a strainer*	7
Colgar un bastón / *to hang a cane*	3080
Colocar un estuche / *to place a pencil case*	19800
Colocar un compás / *to place a compass*	10600
Dar una billetera / *to give a wallet*	26000
Dar un billete / *to give a ticket*	322000
Depositar un rastrillo / *to deposit a rake*	111000
Depositar un mando / *to deposit a controller*	1
Doblar una almohada / *to fold a pillow*	5890

ATTENTIONAL SENTENCES	Co-occurence
Admirar un cartel / *to admire a poster*	3900
Admirar una pulsera / *to admire a bracelet*	3
Adorar un cinturón / *to adore a belt*	2590000
Adorar un jarrón / *to adore a vase*	8490
Apreciar una pistol / *to appreciate a gun*	12500
Apreciar un libro / *to appreciate a book*	88100
Conocer una mochila / *to know a backpack*	228000
Conocer una cartera / *to know a portfolio*	29300
Contemplar una olla / *to contemplate a pot*	9
Contemplar una cacerola / *to contemplate saucepan*	68100
Desear una carpeta / *to desire a folder*	2
Desear una aceitera / *to desire an oil can*	23000
Despreciar un frasco / *to despise a jar*	1
Despreciar la llave / *to despise a key*	1
Distinguir un mechero / *to distinguish a lighter*	5
Distinguir un fósforo / *to distinguish a match*	670000
Divisar un rotulador / *to spot a marker*	12600
Divisar un biberón / *to spot a baby bottle*	14500
Encontrar una pala / *to find a shovel*	78100
Encontrar un fusil / *to find a rifle*	55700
Extraviar una pinza / *to mislay a clamp*	10300

Doblar una servilleta / *to fold a napkin*	56300
Empujar una gaveta / *to push a drawer*	92000
Empujar un carrito / *to push a cart*	13000
Encender una lámpara / *to turn on a lamp*	59100
Encender la radio / *to turn on the radio*	265000
Enjuagar una ensaladera / *to dry a salad bowl*	44400
Enjuagar una cuchara / *to dry a spoon*	403
Guardar una guitarra / *to put away a guitar*	7200
Guardar una flauta / *to put away a flute*	10
Levantar una palanca / *to lift a lever*	22800
Levantar una bandeja / *to lift a tray*	22200
Limpiar una sartén / *to clean a pan*	19000
Limpiar un tarro / *to clean a can*	4800
Llenar una caja / *to fill a box*	70500
Llenar una botella / *to fill a bottle*	81000
Manejar un peine / *to handle a comb*	5010
Manejar un abrelatas / *to handle a can opener*	1700
Manipular una sierra / *to handle a saw*	1840
Manipular un afilador / *to manipulate a sharpener*	2
Mover un lápiz / *to move a pencil*	39200
Mover un bolígrafo / *to move a pen*	10500
Ponerse un sombrero / *to put on a hat*	70700
Ponerse un anillo / *to put on a ring*	33200
Recoger una ficha / *to pick up a token*	13300

Extraviar un alfiler / *to mislay a pin*	2
Gustar una libreta / *to like an agenda*	1
Gustar un plato / *to like a plate*	7010
Imaginar un reloj / *to imagine a watch*	44000
Imaginar un pincel / *to imagine a brush*	7040
Mirar un mapa / *to look at a map*	167000
Mirar una taza / *to look at a mug*	30400
Necesitar una grapadora / *to need a stapler*	521
Necesitar un tenedor / *to need a fork*	13400
Observar un cepillo / *to observe a brush*	15900
Observar un borrador / *to observe an eraser*	15900
Oír un micrófono / *to listen to a microphone*	10500
Oír un video / *to listen to a video*	17800
Olvidar un paquete / *to forget a package*	16000
Olvidar un cuaderno / *to forget a notebook*	8820
Pedir una escoba / *to ask for a broom*	12800
Pedir un salero / *to ask for a salt shaker*	3110
Percibir una jarra / *to perceive a jug*	3
Percibir una campanilla / *to perceive a bell*	1
Perder una gorra / *to lose a cap*	12000
Perder un trapo / *to lose a rag*	29300
Preferir un cortaúñas / *to prefer a nail clipper*	2
Preferir un cajón / *to prefer a cabinet*	8
Querer una tiza / *to want a chalk*	2

Recoger un clavo / *to pick up a nail*	9640
Registrar una maleta / *to search (in) a suitcase*	10100
Registrar un armario / *to search (in) a closet*	5580
Retirar una toalla / *to remove a towel*	8310
Retirar un móvil / *to remove a mobile*	13200
Sacar un jarrón / *to take out a vase*	11600
Sacar un cinturón / *to take off a belt*	47400
Sujetar una lupa / *to grab a magnifying glass*	1230
Sujetar una goma / *to grab a rubber*	2360
Tirar un papel / *to throw a paper*	67400
Tirar un dardo / *to throw a dard*	7560
Utilizar una raqueta / *to use a racket*	14800
Utilizar un hacha / *to use an axe*	30900
Vaciar un tazón / *to empty a large cup*	1310
Vaciar un balde / *to empty a bucket*	2100

Querer un zapato / *to want a shoe*	3820
Rechazar una esponja / *to reject a sponge*	3
Rechazar una chincheta / *to reject a thumbtack*	18200
Reclamar unas tijeras / *to demand a scissors*	6
Reclamar un cuchillo / *to demand a knife*	8
Reconocer una bombilla / *to recognize a light bulb*	4830
Reconocer un martillo / *to recognize a hammer*	9610
Recordar una papelera / *to remember a waste basket*	1
Recordar un sillón / *to remember an armchair*	4
Solicitar un teclado / *to request a keyboard*	25100
Solicitar un taladro / *to request a drill*	10
Tener una batidora / *to have a blender*	130000
Tener una afeitadora / *to have a shaver*	17100
Ver unos auriculares / *to see a headphones*	2220
Ver un sobre / *to see an envelope*	220000

Set 2:

ACTION SENTENCES	**Co-occurence**
Abrir una bolsa / *to open a bag*	367000
Abrir un paquete / *to open a package*	383000
Agarrar un martillo / *to hold a hammer*	9370
Agarrar un cepillo / *to hold a brush*	7850
Agitar un salero / *to shake a salt shaker*	217
Agitar una escoba / *to shake a broom*	673

ATTENTIONAL SENTENCES	**Co-occurence**
Admirar una flauta / *to admire a flute*	1
Admirar una guitarra / *to admire a guitar*	10
Adorar un collar / *to adore a necklace*	8
Adorar un bolso / *to adore a purse*	323
Apreciar un móvil / *to appreciate a mobile*	8310
Apreciar una toalla / *to appreciate a towel*	8120

Apagar un interruptor / *to turn off a switch*	17500
Apagar una aspiradora / *to turn off a vacuum cleaner*	173000
Apretar una chincheta / *to tighten a thumbtack*	0
Apretar una esponja / *to tighten a sponge*	1830
Coger un plato / *to take a plate*	137000
Coger una libreta / *to take an agenda*	119000
Colgar un trapo / *to hang a rag*	8220
Colgar una gorra / *to hang a cap*	2610
Colocar la llave / *to place the key*	421000
Colocar una carpeta / *to place a folder*	74800
Dar unos auriculares / *to give a headphones*	2270
Dar una pinza / *to give a clamp*	80100
Depositar un taladro / *to deposit a drill*	364000
Depositar un teclado / *to deposit a keyboard*	2330000
Doblar un sobre / *to fold an envelope*	7460
Doblar un cartel / *to fold a poster*	4410
Empujar un sillón / *to push an armchair*	2400
Empujar una papelera / *to push a waste basket*	3
Encender un fósforo / *to light a match*	40000
Encender un mechero / *to light a lighter*	12400
Enjuagar una cacerola / *to dry a saucepan*	3
Enjuagar una olla / *to dry a pot*	9
Guardar un cuchillo / *to put away a knife*	35900

Conocer un armario / *to know a closet*	52700
Conocer una maleta / *to know a suitcase*	10
Contemplar una cuchara / *to contemplate a spoon*	6
Contemplar una ensaladera / *to contemplate a salad bowl*	10500
Desear un compás / *to desire a compass*	764000
Desear un estuche / *to desire a pencil case*	1
Despreciar un bolígrafo / *to despise a pen*	184000
Despreciar un tarro / *to despise a can*	162000
Distinguir un tornillo / *to distinguish a screw*	4880
Distinguir una lámpara / *to distinguish a lamp*	14500
Divisar un pastel / *to spot a cake*	3
Divisar una cafetera / *to spot a coffee maker*	106000
Encontrar una bandeja / *to find a tray*	167000
Encontrar una palanca / *to find a lever*	86600
Extraviar un tazón / *to mislay a large cup*	7220
Extraviar una billetera / *to mislay a wallet*	6
Gustar la radio / *to like the radio*	19700
Gustar un sombrero / *to like a hat*	5
Imaginar una goma / *to imagine a rubber*	5560
Imaginar una ficha / *to imagine a token*	12300
Mirar un anillo / *to look at a ring*	24300
Mirar una regla / *to look at a ruler*	22300
Necesitar un peine / *to need a comb*	6160

Guardar unas tijeras / *to put away a scissors*	225
Levantar un fusil / *to raise a rifle*	14000
Levantar una pala / *to raise a shovel*	17300
Limpiar un collar / *to clean a necklace*	7510
Limpiar una jarra / *to clean a jug*	5180
Llenar un bolso / *to fill a purse*	18800
Llenar una taza / *to fill a mug*	54400
Manejar una grapadora / *to handle a stapler*	6
Manejar un pincel / *to handle a brush*	13500
Manipular una campanilla / *to manipulate a bell*	78000
Manipular un cortaúñas / *to manipulate a nail clipper*	73200
Mover un rotulador / *to move a marker*	4
Mover un tenedor / *to move a fork*	9770
Ponerse una pulsera / *to move a bracelet*	9890
Ponerse un reloj / *to put on a watch*	54900
Recoger un mapa / *to pick up a map*	40400
Recoger un alfiler / *to pick up a pin*	11100
Registrar una cartera / *to search (in) a portfolio*	21800
Registrar una mochila / *to search (in) a backpack*	11100
Retirar un libro / *to remove a book*	48200
Retirar una bombilla / *to remove a light bulb*	4500
Sacar una aceitera / *to take out an oil can*	131000
Sacar un frasco / *to take out a jar*	40200

Necesitar una sierra / *to need a saw*	6800
Observar un hacha / *to observe an axe*	10100
Observar un nudo / *to observe a knot*	25000
Oír la aspiradora / *to listen to a vacuum cleaner*	6630
Oír un interruptor / *to listen to a switch*	4
Olvidar un paraguas / *to forget an umbrella*	3590
Olvidar una bolsa / *to forget a bag*	15800
Pedir una castañuela / *to ask for a castanet*	106000
Pedir una lupa / *to ask for a magnifying glass*	10000
Percibir un clavo / *to perceive a nail*	2
Percibir un carrito / *to perceive a cart*	1
Perder un bastón / *to lose a cane*	26900
Perder un colador / *to lose a strainer*	4
Preferir un abrelatas / *to prefer a can opener*	35900
Preferir un afilador / *to prefer a sharpener*	103000
Querer un dardo / *to want a dard*	3
Querer un papel / *to want a paper*	46100
Rechazar un rastrillo / *to reject a rake*	6
Rechazar una coctelera / *to reject a shaker*	142000
Reclamar un lápiz / *to demand a pencil*	7
Reclamar una caja / *to demand a box*	27400
Reconocer una almohada / *to recognize a pillow*	6320
Reconocer la tenaza / *to recognize a pliers*	218000

Sujetar un borrador / *to grab an eraser*	4
Sujetar una pistol / *to grab a gun*	3900
Tirar un zapato / *to throw a shoe*	6620
Tirar una tiza / *to throw a chalk*	1340
Utilizar una afeitadora / *to use a shaver*	4510
Utilizar una batidora/ *to use a blender*	33700
Vaciar un cajón / *to empty a cabinet*	3390
Vaciar un biberón / *to empty a baby bottle*	428

Recordar una gaveta / *to remember a drawer*	546000
Recordar una raqueta / *to remember a racket*	603000
Solicitar un balde / *to request a bucket*	6130
Solicitar un mando / *to request a controller*	19300
Tener una botella / *to have a bottle*	3030000
Tener un cascanueces / *to have a nutcracker*	4570
Ver un billete / *to see a ticket*	166000
Ver una sartén / *to see a pan*	71100

Appendix 3: Sets of sentences used in the second study.

Set 1

ACTION SENTENCES
Ahora sí/no abrirás un cuaderno
Ahora sí/no abrirás un paraguas
Ahora sí/no agarrarás un cascanueces
Ahora sí/no agarrarás la tenaza
Ahora sí/no agitarás una castañuela
Ahora sí/no agitarás una coctelera
Ahora sí/no apagarás un micrófono
Ahora sí/no apagarás un video
Ahora sí/no apretarás un nudo
Ahora sí/no apretarás un tornillo
Ahora sí/no cogerás una cafetera
Ahora sí/no cogerás una regla
Ahora sí/no colgarás un bastón
Ahora sí/no colgarás un colador
Ahora sí/no colocarás un compás
Ahora sí/no colocarás un estuche
Ahora sí/no darás un billete
Ahora sí/no darás una billetera
Ahora sí/no depositarás un mando
Ahora sí/no depositarás un rastrillo
Ahora sí/no depositarás una servilleta
Ahora sí/no doblarás una almohada
Ahora sí/no empujarás un carrito
Ahora sí/no empujarás una gaveta
Ahora sí/no encenderás una lámpara

ATTENTIONAL SENTENCES
Ahora sí/no admirarás un cartel
Ahora sí/no admirarás una pulsera
Ahora sí/no adorarás un cinturón
Ahora sí/no adorarás un jarrón
Ahora sí/no apreciarás un libro
Ahora sí/no apreciarás una pistola
Ahora sí/no conocerás una cartera
Ahora sí/no conocerás una mochila
Ahora sí/no contemplarás una cacerola
Ahora sí/no contemplarás una olla
Ahora sí/no desearás una aceitera
Ahora sí/no desearás una carpeta
Ahora sí/no despreciarás un frasco
Ahora sí/no despreciarás la llave
Ahora sí/no distinguirás un fósforo
Ahora sí/no distinguirás un mechero
Ahora sí/no divisarás un biberón
Ahora sí/no divisarás un rotulador
Ahora sí/no encontrarás un fusil
Ahora sí/no encontrarás una pala
Ahora sí/no extraviarás un alfiler
Ahora sí/no extraviarás una pinza
Ahora sí/no gustarás una libreta
Ahora sí/no gustarás un plato
Ahora sí/no imaginarás un pincel

Ahora sí/no encenderás la radio
Ahora sí/no enjuagarás una cuchara
Ahora sí/no enjuagarás una ensaladera
Ahora sí/no guardarás una flauta
Ahora sí/no guardarás una guitarra
Ahora sí/no levantarás una bandeja
Ahora sí/no levantarás una palanca
Ahora sí/no limpiarás una sartén
Ahora sí/no limpiarás un tarro
Ahora sí/no llenarás una botella
Ahora sí/no llenarás una caja
Ahora sí/no manejarás un peine
Ahora sí/no manejarás un abrelatas
Ahora sí/no manipularás un afilador
Ahora sí/no manipularás una sierra
Ahora sí/no moverás un bolígrafo
Ahora sí/no moverás un lápiz
Ahora sí/no pondrás un anillo
Ahora sí/no pondrás un sombrero
Ahora sí/no recogerás un clavo
Ahora sí/no recogerás una ficha
Ahora sí/no registrarás un armario
Ahora sí/no registrarás una maleta
Ahora sí/no retirarás un móvil
Ahora sí/no retirarás una toalla
Ahora sí/no sacarás un cinturón
Ahora sí/no sacarás un jarrón
Ahora sí/no sujetarás una goma
Ahora sí/no sujetarás una lupa

Ahora sí/no imaginarás un reloj
Ahora sí/no mirarás un mapa
Ahora sí/no mirarás una taza
Ahora sí/no necesitarás una grapadora
Ahora sí/no necesitarás un tenedor
Ahora sí/no observarás un borrador
Ahora sí/no observarás un cepillo
Ahora sí/no oirás un video
Ahora sí/no oirás un micrófono
Ahora sí/no olvidarás un cuaderno
Ahora sí/no olvidarás un paquete
Ahora sí/no pedirás una escoba
Ahora sí/no pedirás un salero
Ahora sí/no percibirás una campanilla
Ahora sí/no percibirás una jarra
Ahora sí/no perderás una gorra
Ahora sí/no perderás un trapo
Ahora sí/no preferirás un cajón
Ahora sí/no preferirás un cortauñas
Ahora sí/no querrás una tiza
Ahora sí/no querrás un zapato
Ahora sí/no rechazarás una chincheta
Ahora sí/no rechazarás una esponja
Ahora sí/no reclamarás un cuchillo
Ahora sí/no reclamarás unas tijeras
Ahora sí/no reconocerás una bombilla
Ahora sí/no reconocerás un martillo
Ahora sí/no recordarás una papelera
Ahora sí/no recordarás un sillón

Ahora sí/no tirarás un dardo	Ahora sí/no solicitarás un taladro
Ahora sí/no tirarás un papel	Ahora sí/no solicitarás un teclado
Ahora sí/no utilizarás un hacha	Ahora sí/no tendrás una afeitadora
Ahora sí/no utilizarás una raqueta	Ahora sí/no tendrás una batidora
Ahora sí/no vaciarás un balde	Ahora sí/no verás unos auriculares
Ahora sí/no vaciarás un tazón	Ahora sí/no verás un sobre

Set 2

ACTION SENTENCES	ATTENTIONAL SENTENCES
Ahora sí/no abrirás una bolsa	Ahora sí/no admirarás una flauta
Ahora sí/no abrirás un paquete	Ahora sí/no admirarás una guitarra
Ahora sí/no agarrarás un cepillo	Ahora sí/no adorarás un collar
Ahora sí/no agarrarás un martillo	Ahora sí/no adorarás un bolso
Ahora sí/no agitarás una escoba	Ahora sí/no apreciarás un móvil
Ahora sí/no agitarás un salero	Ahora sí/no apreciarás una toalla
Ahora sí/no apagarás un interruptor	Ahora sí/no conocerás un armario
Ahora sí/no apagarás una aspiradora	Ahora sí/no conocerás una maleta
Ahora sí/no apretarás una chincheta	Ahora sí/no contemplarás una cuchara
Ahora sí/no apretarás una esponja	Ahora sí/no contemplarás una ensaladera
Ahora sí/no cogerás una libreta	Ahora sí/no desearás un compás
Ahora sí/no cogerás un plato	Ahora sí/no desearás un estuche
Ahora sí/no colgarás una gorra	Ahora sí/no despreciarás un bolígrafo
Ahora sí/no colgarás un trapo	Ahora sí/no despreciarás un tarro
Ahora sí/no colocarás una carpeta	Ahora sí/no distinguirás una lámpara
Ahora sí/no colocarás la llave	Ahora sí/no distinguirás un tornillo
Ahora sí/no darás unos auriculares	Ahora sí/no divisarás una cafetera
Ahora sí/no darás una pinza	Ahora sí/no divisarás un pastel
Ahora sí/no depositarás un taladro	Ahora sí/no encontrarás una bandeja

Ahora sí/no depositarás un teclado
Ahora sí/no doblarás un cartel
Ahora sí/no doblarás un sobre
Ahora sí/no empujarás una papelera
Ahora sí/no empujarás un sillón
Ahora sí/no encenderás un fósforo
Ahora sí/no encenderás un mechero
Ahora sí/no enjugarás una cacerola
Ahora sí/no enjugarás una olla
Ahora sí/no guardarás un cuchillo
Ahora sí/no guardarás unas tijeras
Ahora sí/no levantarás un fusil
Ahora sí/no levantarás una pala
Ahora sí/no limpiarás un collar
Ahora sí/no limpiarás una jarra
Ahora sí/no llenarás un bolso
Ahora sí/no llenarás una taza
Ahora sí/no manejarás un pincel
Ahora sí/no manejarás una grapadora
Ahora sí/no manipularás una campanilla
Ahora sí/no manipularás un cortauñas
Ahora sí/no moverás un rotulador
Ahora sí/no moverás un tenedor
Ahora sí/no pondrás una pulsera
Ahora sí/no pondrás un reloj
Ahora sí/no recogerás un alfiler
Ahora sí/no recogerás un mapa
Ahora sí/no registrarás una cartera
Ahora sí/no registrarás una mochila

Ahora sí/no encontrarás una palanca
Ahora sí/no extraviarás una billetera
Ahora sí/no extraviarás un tazón
Ahora sí/no gustarás la radio
Ahora sí/no gustarás un sombrero
Ahora sí/no imaginarás una ficha
Ahora sí/no imaginarás una goma
Ahora sí/no mirarás un anillo
Ahora sí/no mirarás una regla
Ahora sí/no necesitarás un peine
Ahora sí/no necesitarás una sierra
Ahora sí/no observarás un hacha
Ahora sí/no observarás un nudo
Ahora sí/no oirás la aspiradora
Ahora sí/no oirás un interruptor
Ahora sí/no olvidarás una bolsa
Ahora sí/no olvidarás un paraguas
Ahora sí/no pedirás una castañuela
Ahora sí/no pedirás una lupa
Ahora sí/no percibirás un carrito
Ahora sí/no percibirás un clavo
Ahora sí/no perderás un bastón
Ahora sí/no perderás un colador
Ahora sí/no preferirás un abrelatas
Ahora sí/no preferirás un afilador
Ahora sí/no querrás un dardo
Ahora sí/no querrás un papel
Ahora sí/no rechazarás una coctelera
Ahora sí/no rechazarás un rastrillo

Ahora sí/no retirarás una bombilla
Ahora sí/no retirarás un libro
Ahora sí/no sacarás una aceitera
Ahora sí/no sacarás un frasco
Ahora sí/no sujetarás un borrador
Ahora sí/no sujetarás una pistola
Ahora sí/no tirarás una tiza
Ahora sí/no tirarás un zapato
Ahora sí/no utilizarás una afeitadora
Ahora sí/no utilizarás una batidora
Ahora sí/no vaciarás un biberón
Ahora sí/no vaciarás un cajón

Ahora sí/no reclamarás una caja
Ahora sí/no reclamarás un lápiz
Ahora sí/no reconocerás una almohada
Ahora sí/no reconocerás la tenaza
Ahora sí/no recordarás una gaveta
Ahora sí/no recordarás una raqueta
Ahora sí/no solicitarás un mando
Ahora sí/no solicitarás un balde
Ahora sí/no tendrás una botella
Ahora sí/no tendrás un cascanueces
Ahora sí/no verás un billete
Ahora sí/no verás una sartén