The Default Computation of Negated Meanings

Liuba Papeo[1]*, Jean-Rémy Hochmann[1]*, and Lorella Battelli[2,3]

Abstract

■ Negation is a fundamental component of human reasoning and language. Yet, current neurocognitive models, conceived to account for the cortical representation of meanings (e.g., *writing*), hardly accommodate the representation of negated meanings (*not writing*). One main hypothesis, known as the two-step model, proposes that, for negated meanings, the corresponding positive representation is first fully activated and then modified to reflect negation. Recast in neurobiological terms, this model predicts that, in the initial stage of semantic processing, the neural representation of a stimulus' meaning is indistinguishable from the neural representation of that meaning following negation. Although previous work has shown that pragmatic and task manipulations can favor or hinder a two-step processing, we just do not know how the brain processes an utterance as simple as "I am not writing." We implemented two methodologies based on chronometric TMS to measure motor excitability (Experiment 1) and inhibition (Experiment 2) as physiological markers of semantic access to action-related meanings. We used elementary sentences (Adverb + Verb) and a passive reading task. For the first time, we defined action word-related motor activity in terms of increased excitability and concurrently reduced inhibition. Moreover, we showed that this pattern changes already in the earliest stage of semantic processing, when action meanings were negated. Negation modifies the neural representation of the argument in its scope, as soon as semantic effects are observed in the brain. ■

INTRODUCTION

Negation is a universal, fundamental component of human reasoning and language. Yet, we do not know how the neural representation of a meaning (e.g., *writing*) changes, when that meaning is negated (e.g., *not writing*).

One—perhaps intuitive—hypothesis holds that, for negated meanings, the positive meaning is first fully activated and then modified to reflect negation (e.g., Carpenter & Just, 1975; Russell, 1948). In support of this so-called two-step model of negation, behavioral research has shown that a negative proposition facilitates the processing of the corresponding positive representation. For instance, reading the sentence *"There was no eagle in the sky"* facilitates, in terms of RTs, the recognition of an eagle with outstretched wings (i.e., as if flying in the sky), compared with that of an eagle with folded wings (i.e., as if resting in a nest; Kaup, Yaxley, Madden, Zwaan, & Lüdtke, 2007).

However, these priming effects demonstrate that the positive and the negated representation share features, not that they are *identical*. That is, even if "no eagle in the sky" activates a representation that is more similar to the representation of "an eagle with outstretched wings" than to the representation of "an eagle in a nest", this would be sufficient to induce the observed priming effect.

Moreover, one may argue that a two-step computation of negative statements is a product of certain tasks only. For example, the task of judging whether an object in a picture (e.g., an eagle) was mentioned in the previous sentence (*"there is an eagle in the sky"*) may solicit the formation of a mental visual image of the sentence content during reading. Because negative statements (*"there is no eagle in the sky"*) most often point to open-ended sets of possibilities (e.g., if there is no eagle in the sky, there could be a cloud, the sun, the moon, a plane, etc., and the eagle could be in the nest, on a tree, diving in water, and so on), the simplest strategy to perform *this* task would be to imagine an eagle in the sky, though knowing that it corresponds to the counterfactual statement. This strategy would resolve in faster recognition of the picture of an eagle in the sky than the picture of an eagle in a nest. In fact, other studies have shown that the number of possibilities opened by a negative sentence modulates the extent to which the representation of the corresponding positive statement is activated (Orenes, Beltrán, & Santamaría, 2014).

Furthermore, behavioral (e.g., Nordmeyer & Frank, 2015; Tian, Breheny, & Ferguson, 2010), eye-tracking (e.g., Orenes, Moxey, Scheepers, & Santamaría, 2015), and ERP (e.g., Nieuwland & Kuperberg, 2008) studies, tracking the time course of language processing, have questioned the necessity of an extra processing stage, which would make negation inherently harder than affirmation. This research has focused on sentence processing and on the factors that could make negation harder to process than affirmation,

or not. Although the field is not clear of controversy (see, e.g., Lüdtke, Friedrich, De Filippis, & Kaup, 2008), there is clear indication that negation is not hard to process when pragmatics favors its interpretation, and it is hard only when pragmatically infelicitous (e.g., Nordmeyer & Frank, 2015). This interim conclusion, however, does not necessarily rule out the two-step model; in fact, this model could illustrate the default way in which an argument preceded by negation is processed, *unless* certain (facilitating) pragmatic conditions are met.

Thus, the question remains: What is the default computation of negation? What happens when individuals are not asked to judge whether a picture corresponds to a statement, or when no pragmatic elements constrain the interpretation of words' meanings? In the current study, we addressed this issue in a pragmatically neutral context, during a passive reading task.

A stringent test of the two-step model is to determine whether, in the initial stage of semantic retrieval, the neural representation of a stimulus' meaning is indistinguishable from the neural representation of that meaning when preceded by negation. Previous studies on the effects of negation on semantic-related neural activity do not offer a conclusive response. The earliest—known—changes associated with negation have been reported in neural components (i.e., the ERP component N400) that could index indistinctly the costs of semantic retrieval and of integration of semantics and pragmatics (Nieuwland & Kuperberg, 2008). Another set of studies reported changes in the level of neural activity for negative versus affirmative sentences but, with the methodologies employed (functional MRI or analysis of brain oscillations), they could not distinguish between different stages (or steps) of processing (Alemanno et al., 2012; Tomasino, Weiss, & Fink, 2010; Christensen, 2009; Tettamanti et al., 2008). Using various methodologies, other studies measured differences in the physiological correlates of processing positive versus negated words, from 600 msec after the word onset onward (Foroni & Semin, 2013; Aravena et al., 2012; Liuzza, Candidi, & Aglioti, 2011). This latency, way beyond the onset of the word's semantic retrieval (200–250 msec; e.g., Pylkkänen & Marantz, 2003; Kutas & Federmeier, 2000), leaves the earlier effects of negation undecided.

In the last set of studies, the search for a temporal characterization of the effects of negation on semantic-related neural activity took advantage of the peripheral effects of processing words' meanings with concrete motor components. In fact, during processing words describing motor actions, the motor portion of the left precentral gyrus (LPCG) is recruited by language semantic regions (e.g., in the temporal cortex) in the earliest stage of semantic access (within 250 msec from the word onset; Papeo et al., 2014). Extensive research on this neural phenomenon holds that increased LPCG activity is a signature of semantic access to the motor features of a word meaning (for reviews, see Kemmerer, in press;

Papeo, Pascual-Leone, & Caramazza, 2013; Papeo & Hochmann, 2012; Pulvermüller, 2005). Following this line, in two experiments, we measured motor excitability and inhibition, as physiological markers of semantic access to action-related meanings.

In Experiment 1, we used chronometric TMS to obtain a punctual measure of LPCG activity (i.e., motor excitability) at different points in time, while participants read verbs preceded by a positive context word ("ora scrivo", *Now I write*) or a negative one ("non scrivo", *I don't write*). Thus, using LPCG as a window into the semantic network of action-related words, we studied whether and when negation changes the neural representation of a word meaning. Initial (and comparable) increase of motor excitability for action and negated action meanings, followed by a selective decrease for negated meanings, would be evidence in favor of the two-step model of negation. An initial difference between positive and negated meanings would rather hold that negation is incrementally incorporated to construct a meaning.

In Experiment 2, we addressed the hypothesis of a link between the processing of negation and inhibitory mechanisms, which has been recurrently suggested in philosophy and psychology (e.g., Vandamme, 1972; Russell, 1948) but never investigated directly. In particular, we considered the possibility that negation changes the nature of the neural coding, increasing inhibitory activity, rather than excitability. In effect, should one find reduced motor excitability for negated words, it would remain possible that LPCG is still recruited and participates to processing meaning, but through inhibitory activity. To measure motor inhibitory activity for action and negated action meanings, we took advantage of another TMS paradigm, which offers a unique opportunity to measure inhibition, an otherwise silent (i.e., difficult to quantify) neural mechanism.

EXPERIMENT 1: METHODS

Participants

Eighteen right-handed, native Italian speakers (16 women; age range = 19–35 years) participated as paid subjects. All had normal or corrected-to-normal vision, were clear of contraindications to TMS (Rossi, Hallett, Rossini, Pascual-Leone, & Safety of TMS Consensus Group, 2009), and gave informed consent. The study was approved by the ethics review board of the University of Trento. Four additional participants were discarded for not following the experimenter's instructions (2), for a machine failure (1), or for unforeseen noisy maintenance operations in the proximity of the experimental room (1).

Materials

Stimuli were 80 Italian verbs, 40 describing a manual action (e.g., *writing*) and 40 denoting a physical or psychological

state (e.g., *wondering*). These items were taken from a larger database including 375 verbs rated for action relatedness and for association with a specific bodily effector (hand, foot, head, or whole body; for details, see Papeo, Vallesi, Isaja, & Rumiati, 2009). The selected action and state verbs were presented in the first person of the present tense. They were matched for agreement on the action-state categorical distinction (mean for action verbs: 96%; for state verbs: 94%; $t(39) = -1.34, p = .19$), length (number of graphemes; $t(39) = -1.48, p = .14$), and frequency (CoLFIS; Bertinetto et al., 2005; $t(39) = 1.39, p = .17$).

During the experiment, each item appeared four times, twice preceded by the adverb "*ora*" (*now*) and twice preceded by the adverb "*non*" (*don't*), for a total of 320 trials. The adverb defined each trial's context as positive (*ora*) or negative (*non*). Being Italian, a pronoun-dropping language, the pronoun is optional and was not shown.

Procedures

TMS was delivered over the LPCG to obtain a punctual measure of corticospinal excitability at different points in time, while participants read phrases consisting of a verb preceded by a positive context word ("ora scrivo", *Now I write*) or a negative one ("non scrivo", *I don't write*).

Each trial began with the context word (250 msec), followed by a blank (200 msec) and then a verb (700 msec). In compliance with the norms for the use of TMS, the interval between two consecutive trials lasted 6 sec. Single-pulse TMS was delivered over the hand representation in the left primary motor cortex, the posterior aspect of the LPCG, to induce twitches in the peripheral muscle responding to the stimulated area (i.e., right first dorsal interosseous [rFDI]). This peripheral effect of TMS is punctual, and the amplitude of muscle activity, recorded in the form of motor-evoked potentials (MEPs), correlates positively with corticospinal excitability. TMS was delivered 200 msec after the onset of the context word or at one of three different delays from the verb onset, separated by 150 msec, and starting from 250 msec (i.e., 250, 400, and 550 msec). The 250-msec delay corresponds to the onset of the effects of words' semantics in the brain (Lau, Phillips, & Poeppel, 2008; Kellenbach, Wijers, Hovius, Mulder, & Mulder, 2004; Pylkkänen & Marantz, 2003; Kutas & Federmeier, 2000), including word-related motor activity (Papeo et al., 2013).

TMS was delivered through a 70-mm figure-of-eight coil connected to a Magstim Rapid2 Stimulator (Magstim, Withland, UK) and kept tangential to the scalp surface. The optimal scalp position to induce MEPs in the rFDI was identified around the C3/C4 reference point of the international 10–20 EEG system and marked on a cap worn by the participant. The stimulation intensity was adjusted at 120% of the individual resting motor threshold, defined as the minimum intensity to evoke MEPs with ≥50 μV peak-to-peak amplitude in the relaxed muscles in at least three of five consecutive pulses (Rossini et al., 1994). Group mean motor threshold was 58 ± 8% of the maximum stimulator output. MEPs were recorded through gold surface electrodes placed over the rFDI (active electrode), the metacarpophalangeal joint of index finger (reference), and the ventral surface of the right wrist (ground). The EMG signal was recorded with a 10-kHz sampling rate, amplified, filtered (20–2500 Hz band pass), and transferred to a second computer for online monitoring and offline analysis (LabChart software, ADInstruments, Sydney, Australia).

Participants sat in front of a screen (~70 cm away) where stimuli appeared in random order (black ink, Courier New 96, white background). They were instructed to keep their right hand still and relaxed on their lap and to read silently the verbs during the TMS session to perform a delayed recognition test (see below). Stimulus presentation and synchronization with TMS and EMG systems were controlled through MATLAB (The MathWorks, Inc., Natick, MA). After the 50% of the trials was shown, participants could take a break.

After the TMS session, a recognition test was administered, including 20 action and 20 state verbs, randomly selected from the experimental list ("old" items), and 40 "new" items (20 manual action and 20 state verbs) matched for length and frequency with the "old" ones ($ps > .05$). Each trial begun with a fixation cross (200 msec) followed by the verb. Participants had to decide whether they had seen a verb during the TMS session by pressing one of two keys (yes or no). The item remained on the screen until a response was given.

Performance significantly above the chance level (50%, binomial test, $α = 0.05$) was the criterion to include a participant in the MEP analysis. The statistics was carried out on MEP peak-to-peak amplitude values (mV) within 1.5 *SD* from the individual mean (92% of the total MEPs) using ANOVA and Fisher's least significant difference tests for post hoc comparisons.

EXPERIMENT 2: METHODS

Participants

Fourteen female right-handed, native Italian speakers (age range = 19–35 years) participated as paid subjects. All were clear of contraindications to TMS and gave informed consent. The study was approved by the ethics review board of the University of Trento. Four additional participants were discarded, two because of a machine failure during TMS, one because she performed below chance in the recognition test (see below), and one because she reported discomfort during TMS and did not complete the experiment.

Materials and Procedures

Stimuli, task, and procedures were identical to Experiment 1, except for two features. First, TMS was delivered with two delays (instead of four): 200 msec after the context word onset (*ora* or *non*) and 250 msec after the verb onset. Therefore, each stimulus was repeated twice for a total of 160 trials.

Second, participants were instructed to maintain an isometric tonic contraction of the rFDI muscle throughout the experiment. When the muscle targeted by TMS is voluntarily contracted, the MEP is followed by a suppression of EMG activity, called cortical silent period (CSP; Figure 1D). CSP duration correlates positively with the activity of GABAergic inhibitory neurons (Schütz-Bosbach, Avenanti, Aglioti, & Haggard, 2009; Inghilleri, Berardelli, Cruccu, & Manfredi, 1993; Cantello, Gianelli, Civardi, & Mutani, 1992). Before the experiment, participants were trained to maintain the 20% of their maximal contraction using as feedback their own EMG signal shown on a screen. To maintain this contraction during TMS, they were instructed to contract the rFDI against a rubber band around the right fingers and keep the index fingertip in contact with a marker on the tabletop (see also Schütz-Bosbach et al., 2009).

Compliance with this instruction and a performance significantly above chance in the recognition test were the criteria to include a participant in the CSP analysis. This analysis was carried out on the CSP duration values (msec) within 2 *SD* from the individual condition means (96% of the data).

The CSP duration was determined by an automated algorithm implemented in MATLAB, as follows. For each trial, the amplitude of the signal during the 200 msec preceding the TMS trigger was computed and served as baseline. The beginning and the end of the CSP were defined as the time point of the MEP positive peak and the time point when the EMG signal returned to the 25% of the baseline amplitude, respectively (see Figure 1D).

RESULTS

Experiment 1

All 18 participants succeeded in the recognition task ($ps > .001$) and were included in the analysis.

A 2 Context (positive, negative) × 2 Semantic Category (action, state) × 3 Timing (250, 400, 550 msec) repeated-measures ANOVA yielded a Context by Semantic Category interaction, $F(1, 17) = 8.32$; $p = .010$ (Figure 1A). MEP amplitude was greater for action than for state verbs in the positive ($p = .013$), but not in the negative context ($p = .21$). Moreover, MEP amplitude for action verbs was greater in the positive than in the negative context ($p = .021$). This pattern was not modulated by Timing (Context × Semantic Category × Timing: $F(2, 34) = 0.62$; $p = .54$; Figure 1B).

A separate ANOVA was performed, including only the MEPs measured at the earliest probed timing (250 msec). This analysis again showed a significant Context × Semantic Category interaction, $F(1, 17) = 5.74$; $p = .028$. Although the comparison between positive and negated
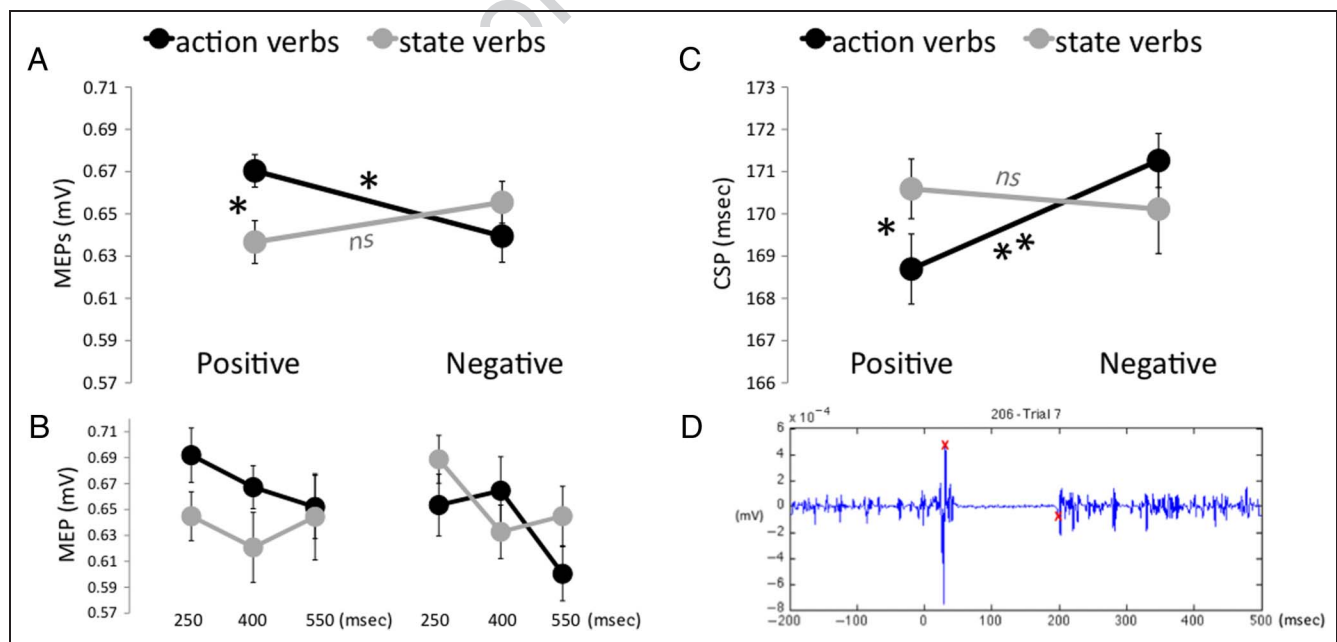
Figure 1. (A) Mean MEPs for action and state verbs in the positive and negative contexts, averaged over time, and (B) as a function of time intervals. (C) Mean CSP duration for action and state verbs in the positive and negative contexts. Error bars denote within-subject standard errors. (D) Example of the data for a single trial of one participant, in Experiment 2 (Participant ID 206; Trial 7). Time 0 denotes TMS delivery. Red crosses indicate the beginning and the end of the CSP as detected by our automated algorithm. **$p < .01$; *$p < .05$; *ns, $p ≥ .14$.

action verbs at 250 msec did not reach significance ($p >$ .05), the significant interaction confirmed that the context (positive or negative) modulated the difference in MEP amplitude between action and state verbs (0.047 mV in the positive context and −0.035 mV in the negative context), already at 250 msec.

One might wonder whether 550 msec is outside the time interval for lexical-sematic access, and it rather corresponds to a change in the representation of the stimulus, related, for example, to the onset of integration processes or inferences based on the language input (e.g., see Papeo et al., 2009). We addressed this issue in a new ANOVA without the third level of the Timing factor (550 msec). This analysis confirmed a significant interaction between Context and Semantic Category, $F(1, 17) = 7,753$, $p = .012$, and showed a main effect of the Timing, $F(1, 17) = 8.057$, $p = .011$, but no interaction between Timing and the other factors ($ps > .280$).

Finally, we analyzed the effect of TMS over LPCG during the presentation of the context word. A t test showed no difference in the MEP amplitude in response to the positive and negative context word, $t(17) = .86$; $p = .40$; that is, the two context words (*ora* and *non*), on their own, did not trigger different levels of motor excitability.

Experiment 2

One participant performed significantly below chance in the recognition test ($p < .05$) and was discarded from the analysis. For the remaining 14 participants, a repeated-measures ANOVA yielded a Context × Semantic Category interaction, $F(1, 13) = 10.27$; $p = .007$ (Figure 1C): CSP was shorter for action than for state verbs in the positive ($p = .014$), but not in the negative context ($p = .11$); moreover, it was shorter for action verbs in the positive context, relative to the same verbs in the negative context ($p = .002$).

A t test showed no difference in CSP duration in response to the positive ($M = 175.10$ msec) and negative ($M = 173.78$ msec) context word; $t(13) = 0.77$; $p = .45$.

DISCUSSION

Results of Experiment 1 showed the effect of increased motor excitability (i.e., MEP amplitude) in response to action-related verbs, as compared with state verbs. Moreover, we exploited the temporal resolution afforded by TMS and measured TMS-induced MEPs to study whether and when negation modifies the network representing the meaning of the word in its scope. The results showed that, already at the earliest probed timing (250 msec after the word onset), the context (positive or negative) affected the processing of action verbs more strongly than the processing of state verbs. Overall, the MEP amplitude for negated action verbs was lower than the MEP amplitude for the same items in the positive context and did

not differ from the MEP amplitude associated with state verbs; the processing of state verbs was not affected by the context. Thus, negation modifies the network representing action words from the first step of semantic processing. It appears to act by blocking (i.e., abolishing) the retrieval of—at least some—components of a word meaning, such as the motor features of action-related words, whose retrieval is normally indexed by enhanced LPCG activity (for reviews, see Kemmerer, in press; Papeo & Hochmann, 2012; Binder & Desai, 2011).

But is the recruitment of information in LPCG truly blocked? In Experiment 2, we hypothesized that negation changes the nature of the neural coding, increasing inhibitory activity, rather than excitability. To test this, we implemented a TMS paradigm to measure motor inhibition in the form of CSP duration. Extensively used in relation to motor tasks (e.g., Inghilleri et al., 1993; Cantello et al., 1992), the current paradigm proved sensitive to changes induced by higher-level tasks such as word processing. Thus, our results offer, for the first time, a complete picture of action word-related motor activity, characterized by selectively increased excitability (Experiment 1) and concurrently reduced inhibition of the motor cortex (Experiment 2) for action verbs. This pattern of excitatory and inhibitory activity changes when action meanings are negated. In particular, the cortical representations of a positive and a negated action meaning are distinguishable as soon as semantic effects are observed in the brain (250 msec after verb onset).

The fast change in the configuration of the brain network representing the concept in the scope of negation refutes the two-step model. This model, whereby a semantic representation is first fully activated and then suppressed to reflect negation, has been questioned in studies showing no costs of processing negation (vs. affirmation), when the sentential context anticipated and/or constrained its interpretation (e.g., Nordmeyer & Frank, 2015; Tian et al., 2010; Nieuwland & Kuperberg, 2008). In the current study, the view of two necessary steps for processing negation is challenged without any manipulation of pragmatic factors. This implies that negation is processed incrementally not only when it is pragmatically licensed or felicitous, in a rich sentential context, but also when it occurs in an impoverished sentential context (*non* + verb).

But, is 250 msec really early? One might ask whether 250 msec is indeed a quite late interval and we might have missed the first of the two putative steps, when the semantic network activation would be just identical for action and negated action words. Had we tested an earlier interval with TMS, our expectation is that we would not have found a difference between action and negated action words, insomuch that we would not have found a difference between action and state words. In fact, if word reading elicits earlier (<250 msec) effects in the brain, these typically reflect visual shape recognition, lexical and morphological features, or syntactic

categorization (e.g., the M170 observed in MEG studies or the early LAN, ELAN, found in EEG studies; e.g., Dikker, Rabagliati, & Pylkkänen, 2009; Friederici & Weissenborn, 2007; Pylkkänen & Marantz, 2003). There seems to be no relation between these effects and the access to words' semantics. The known earliest effects of words' semantics are the N400 in EEG (starting around 250 msec from word onset and peaking at ~400 msec; Kutas & Federmeier, 2000), the M350 (~350 msec) and possibly the M250 (~250 msec) in MEG (Pylkkänen & Marantz, 2003), and the LPCG activity in TMS studies (250 msec; Papeo et al., 2009, 2014). Therefore, we can be confident that, by measuring LPCG activity at 250 msec, we tapped the early stage of semantic processing.

Finally, to address the question as how a negated meaning is represented, our results offer an indication that the negative counterpart of a meaning is constructed in part by blocking the access to some neural information related to the positive meaning. This view, suggested in other studies (e.g., Bartoli et al., 2013; Foroni & Semin, 2013; MacDonald & Just, 1989), earns credence here, because our measure of inhibition, unprecedented in this field, could demonstrate that the recruitment of LPCG is truly blocked and not expressed through inhibitory activity. In other words, because neither motor excitability nor inhibitory activity for negated action verbs reliably differed from the baseline/control condition (here, state verbs), we hypothesize that, in case of negation, the LPCG is *blocked*. Although the extent of this *blockage* within the network and beyond LPCG remains unknown, our results demonstrate that "*not*" before a verb prevents processes that would have otherwise occurred, such as the retrieval of specific (e.g., motor) features of a meaning in regions such as the LPCG. The case study of action-related words may open to new research to investigate the effect of negation on semantic contents that could recruit modality-specific systems other than the motor one (e.g., visual such as *red* or emotional such as *happy*) and on different features of meanings (sensory-motor vs. non-sensory-motor, more abstract features).

In summary, previous investigation of negation processing has gathered critical observations but also a number of unsolved questions. Some authors have reported evidence in favor of two sequential processing steps (e.g., Kaup et al., 2007), but their tasks may have artificially favored such computation strategy (Orenes et al., 2014). Others have suggested that pragmatic factors determine the incremental incorporation of negation in the meaning, which, in turn, does not require two processing steps (e.g., Tian et al., 2010; Nieuwland & Kuperberg, 2008). Here, we have investigated the default computation of negation. We have shown that, in a passive reading task, in the absence of pragmatic manipulation, individuals process elementary negative sentences (negation + verb), without resorting to two steps. Rather, negation is reflected in the activity of the semantic network, as soon as the effects of word semantics arise in the brain.

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