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Language sensorimotor specificity modulates the motor system

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ABSTRACT

Embodied approaches to language understanding hold that comprehension of linguistic material entails a situated simulation of the situation described. Some recent studies have shown that implicit, explicit, and relational properties of objects implied in a sentence are part of this simulation. However, the issue concerning the extent to which language sensorimotor specificity expressed by linguistic constituents of a sentence, contributes to situating the simulation process has not yet been adequately addressed. To fill this gap, we combined a concrete action verb with a noun denoting a graspable or non-graspable object, to form a sensible or non-sensible sentence. Verbs could express a specific action with low degrees of freedom (DoF) or an action with high DoF. Participants were asked to respond indicating whether the sentences were sensible or not. We found that simulation was active in understanding both sensible and non-sensible sentences. Moreover, the simulation was more situated with sentences containing a verb referring to an action with low DoF. Language sensorimotor specificity expressed by the noun, played a role in situating the simulation, only when the noun was preceded by a verb denoting an action with high DoF in sensible sentences. The simulation process in understanding non-sensible sentences evoked both the representations related to the verb and to the noun, these remaining separated rather than being integrated as in sensible sentences. Overall our findings are in keeping with embodied approaches to language understanding and suggest that the language sensorimotor specificity of sentence constituents affects the extent to which the simulation is situated.

1. Introduction

In the last decade the "embodied" view to language understanding has begun to challenge the classical view, according to which comprehension of linguistic material derives from an arbitrary correspondence between abstract symbols, internally represented in an amodal/propositional way, and their corresponding extensions in the world (e.g., Fodor, 1975). The embodied view assumes that language comprehension makes use of the neural systems ordinarily used for perception, action and emotion (Barsalou, 1999; Barsalou and Wiemer-Hastings, 2005; Gallese, 2003, 2008; Gallese and

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Lakoff, 2005; Glenberg, 1997; Glenberg and Robertson, 1999; Glenberg and Kaschak, 2002; Lakoff, 1987; Lakoff and Johnson, 1980, 1999; Pulvermüller, 1999, 2002, 2005; Rizzolatti and Gallese, 1997).

Focusing on language material related to concrete actions, recent neurophysiological studies have shown that premotor neurons are involved during language processing (for a review see for example Hauk et al., 2008; Willems and Hagoort, 2007). In an event-related fMRI study, Hauk et al. (2004) showed that silent reading of verbs referring to face, leg, and arm actions led to an activation of different sectors of the premotor area, strictly depending on the effector involved in the read action-related words. With the same technique, Tettamanti et al. (2005) found a very similar somatotopic activation of the premotor cortex using a listening task in which sentences expressing action performed with the mouth, foot, and hand were used. Also in keeping with the involvement of the premotor cortex in action-related language material processing are the results collected by Buccino et al. (2005) in a single-pulse transcranial magnetic stimulation (TMS) study, which showed that motor-evoked potentials (MEPs) recorded from hand and foot muscles are modulated during listening to hand- and foot-related action sentences, respectively. Further evidence for an activation of the premotor cortex while processing language material denoting actions involving the leg or face comes from a high-density magneto-encephalography (MEG) study carried out by Pulvermüller et al. (2005) who showed that this activation occurs within 170 msec after the auditory presentation of action-related words. Taken together these findings support the idea that the recruitment of sensorimotor areas during the processing of linguistic material, entails a simulation process that is sensitive at least to the effector used to perform the action described in the linguistic material.

However, it is an open question whether the recruitment of sensorimotor areas is a necessary requisite to understanding language or rather a side effect of distinct cognitive processes underlying it. In order to clarify this issue, Sato et al. (2008) demonstrated that the recruitment occurs only when an explicit semantic representation is required by the task. This result is well expressed by the LASS theory (Simmons et al., 2008) which proposes that both a linguistic processing and a situated simulation are active during language coding. Different mixtures of linguistic processing and simulation occur depending on stimuli and task conditions. According to LASS theory, a situated simulation is activated only when the meaning of the linguistic material has to be retrieved in order to perform the task. This simulation, rather than reproducing a generic situation, is assumed to represent the situation to which the linguistic material refers, in a situated manner. For example, when the word "dog" is presented, simulation does not represent an unspecific dog, but represents a specific dog in a particular setting that contains definite agents, objects, actions, events, and mental states. This assumption of the LASS theory could be considered to be quite demanding if one takes into account the fact that language does not provide analog online temporal information about the properties of the situation to which language refers. As it has already been pointed out by Buccino et al. (2005), this lack of analog information plausibly means that situated simulation could be highly stereotyped, representing the most frequently experienced situation implied by language, or, alternatively, more diffuse than it is assumed by the LASS theory.

A growing body of empirical work has emerged investigating the extent to which the simulation process, active during language comprehension, is situated. Some behavioral studies have demonstrated that both implicit (e.g., shape, size, and color) and explicit (e.g., orientation) properties of objects, implied in a sentence, are part of the mental simulation of the situation described. Using a recognition paradigm, Zwaan et al. (2002) found that subjects were faster to decide whether an object represented in a picture had been mentioned in a preceding sentence when there was a match between the shape of the pictured object and the shape of the object implied in the sentence. For example, the sentence "The ranger saw the eagle in the sky" induced a faster recognition for the picture of an eagle with outstretched, rather than folded, wings. With the same paradigm, Standfield and Zwaan (2001) demonstrated that recognizing the orientation of pictured objects was speeded when the orientation matched the one implied by a preceding sentence. In a kinematic study, Gentilucci and Gangitano (1998) showed that adjectives denoting size, such as "long" and "short", printed on the visible face of a rod significantly affected the reaching component of grasping movements directed toward the rod, even though word reading was not explicitly required. Among evidence consistent with the idea of a situated simulation during language understanding there are also those recently collected by Richter and Zwaan (2009) who found that reading color words speeded the discrimination of matched test colors.

In addition, a number of studies have shown support for the notion that representations simulated during sentence comprehension also take into account properties pertaining to actors, and their interactions with objects, involved in the scenario described. For example, Borghi et al. (2004) demonstrated that the attribution of an object denoted by a noun, such as "sign", to a certain location, was faster if the noun referred to an object more easily available in the subject's perspective, implied by a preceding sentence (e.g., "You are waiting outside a restaurant" *vs* "You are eating in a restaurant"). Using a sensibility judgment task, Glenberg and Kaschak (2002) found that responses to sensible sentences expressing a movement toward or away from the subject were performed more rapidly when a movement in the same direction as that described in the sentence was required in order to give the response. Further evidence in support of a situated simulation during language understanding was provided by Tucker and Ellis (2004) who found faster responses in categorizing the referents of nouns into natural objects or artefacts when the response movements reproduced the particular kind of grip (i.e., precision or power grip) typically used to grasp the test objects. Furthermore, Borghi and Scorolli (2009) recently found a facilitation of the dominant hand in responses to sensible hand-related action sentences and concluded that simulation is sensitive to the specific hand the action expressed by the sentence typically involves.

All these findings strongly support the idea that the simulation process during language understanding

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reproduces in a situated manner the scenario described. These studies have, however, suffered a major shortcoming: linguistic material, which consisted most often of elaborated sentences, and experimental designs used did not allow one to address the issue of what makes the simulation situated. Given the lack of analog information in language, it is possible to hypothesize that the greater the number of lexical elements in the sentence, the more simulation is situated.

Alternatively, it is plausible that linguistic elements from a particular grammar category, such as that of verbs and nouns, are more effective than others for situating simulation during language comprehension. This possibility is in keeping with the so-called linguistic focus hypothesis (LFH, Zwaan and Taylor, 2006; Taylor and Zwaan, 2008) according to which simulation during sentence understanding does not extend beyond the verb that specifies the action or, at any rate, beyond the linguistic constituent that immediately follows the verb and better specifies the described action, such as manner-oriented adverbs. Linguistic constituents that code for different elements of the described situation, such as those expressing context and acted-upon objects, shift attention away from the action itself and are responsible for the extinction of the simulation process.

A third possibility is that the specificity of simulation is a function of the degrees of freedom (DoF) of the motor program related to the action expressed by the linguistic constituents of a sentence, independently of their grammar category. The concept of DoF, typically conceived as the number of dimensions in which a movement (e.g., a grasping movement) can vary, has been exploited here to make more intuitive the understanding of sensorimotor specificity of complex actions. To investigate the role played by DoF of actions expressed by language material in simulation, we used, in a sensibility judgment task, sensible and non-sensible sentences formed by concrete verbs and nouns, each expressing a behavioral event related to a motor program with high or low DoF. Specifically, two categories of concrete action verbs were selected. Verbs in the first category, termed action Verbs with low DoF (VLDoF), referred to a specific and observable behavioral event performed on a specific class of objects by specific actors. These verbs maintain a reference to a particular context and situation. In addition, all actions to which a specific VLDoF can be applied, share a common physically invariant feature. For example, all actions that can be described by "to rake" involve both hands as a physically invariant feature. In contrast, verbs in the second category, termed action Verbs with a high DoF (VHDoF), referred to an observable behavior that can be performed on several objects by numerous actors in very many different ways and situations. Although all behavioral events to which a specific VHDoF can be applied have the same meaning, they do not share specific physically invariant features. For example the VHDoF "to waste" does not allow us to unambiguously visualize a specific behavior, object, actor, kind of effector, and context, as the VLDoF "to rake" does[1]. Action verbs with either low or high DoF were combined with concrete nouns denoting graspable or non-graspable objects (e.g., "the key" *vs* "the wind"). As compared with nouns referring to non-graspable objects, nouns referring to graspable objects express a motor program with lower DoF, given that they directly imply manual movements of grasping and fine manipulation.

By combining VLDoF and VHDoF with nouns referring to graspable and non-graspable objects we constructed sensible and non-sensible sentences expressing an action characterized by a motor program with a decreasing DoF. We reasoned that if the amount of sensorimotor specificity expressed by the sentence is effective in situating the simulation process, then a decrease of response time in judging sentence sensibility should be observed as the number of the linguistic constituents expressing an action with a low DoF increases. Moreover, comparisons among sentences in which both the constituents, only one of the constituents, or no constituents, express a motor program with a low DoF, should allow us to disentangle the relative weight and role of verbs and nouns in situating the simulation process during language understanding. In addition, the linguistic material and the experimental design used in the present study should also allow us to explore the nature of simulation, if any, during the understanding of sentences that express a situation that does not make sense.

Although a mass of empirical evidence from behavioral, neurophysiological and brain imaging studies has extensively shown support for the idea that the meaning of goal-directed actions, either observed or described by language, is understood by means of a simulation mechanism that automatically evokes the motor representation of these actions in the observer (e.g., Rizzolatti et al., 2001), listener or reader (Gallese and Lakoff, 2005), it is still an open question whether this mechanism also induces the understanding of behavioral events that do not make sense since they cannot actually be performed. In a fMRI study, Buccino et al. (2004) showed that the simulation mechanism was used to understand the meaning of observed actions belonging to the motor repertoire of a human observer (e.g., biting and speech reading), whereas a mechanism based on visual recognition drove meaning retrieval of actions that do not belong to the motor repertoire of the observer (e.g., barking). In contrast, Costantini et al. (2005), using the same technique, found that observation of both possible and biomechanically impossible movements of fingers induced a selective recruitment of motor-related cortical areas that map body actions, thus indicating that the simulation mechanism is active even when observed behavioral events violate the constraints of human anatomy. Similar results were also collected in a single-pulse TMS study by Romani et al. (2005) who showed that MEPs recorded from muscles that would be involved in the actual execution of actions of the right index and little fingers are facilitated during the observation of movements performed using these fingers, independently of their biomechanical plausibility.

As far as we know, there are no available studies specifically designed to explore whether a simulation process induces the understanding of written sentences expressing a behavioral event that cannot be actually performed by the reader. To fill this gap, we reasoned that if a simulation

[1] It is worth noting that our distinction between VLDoF and VHDoF almost overlaps with the classification into descriptive and interpretative action verbs described in the Linguistic Category Model by Semin and Fiedler (1988).

mechanism is not active during the understanding of sentences that do not make sense, then response time in judging non-sensible sentences should not be modulated by the DoF expressed by their linguistic constituents. In contrast, if a simulation process is active during understanding of non-sensible sentences, then it might reasonably evoke the feasible sensorimotor representation closest to those related to the verb or the noun. For example, the non-sensible sentence "to squeeze the sunset" could activate either the representation of squeezing an orange or a lemon, or, alternatively, the representation of watching or painting the sunset. If this is true, then an effect of the amount of DoF expressed by either the verb or the noun on response time measured for non-sensible sentences should be observed. Another possibility is that the simulation process during the understanding of non-sensible sentence might evoke both the representations related to the verb and the noun, separately. For instance, the sentence "to squeeze the sunset" might activate the motor representation of squeezing and the perceptual representation of the sunset. In this case, the main effects of the amount of DoF expressed by the verb and the noun on response time measured for non-sensible sentences should be observed.

2. Methods

2.1. Participants

Twenty-four participants (3 males and 21 females) were recruited as volunteers in accordance with the Declaration of Helsinki. They were all students of the University of Parma (mean age ± SD, 21.5 ± 3.03 years), native Italian Speakers and right-handed according to the Edinburgh Handedness Questionnaire (Mean Score ± SD, .87 ± .11, Oldfield, 1971). All participants had normal or corrected-to-normal vision, and reported no history of speaking and/or motor disorders. All participants were naïve as to the purpose of the study, and gave their informed consent prior to testing.

2.2. Materials

Materials consisted of word pairs composed of an action verb, conjugated in the infinite tense, followed by a concrete noun. Half of the verbs referred to single actions typically performed by specific actors on a particular class of objects in definite contexts (e.g., to water, to sign, to seed, etc.). Since they expressed actions characterized by a motor program with a low DoF, these verbs were termed as VLDoF. Verbs from the other half referred to single actions that can be performed in very many ways and contexts by a myriad of actors on countless objects (e.g., to book, to recycle, to wait for, etc.). Since they expressed actions characterized by a motor program with a high DoF, these verbs were termed as VHDoF. Half of the action verbs from each category were paired with nouns referring to concrete non-graspable objects and the other half were paired with nouns referring to concrete graspable objects. For example, the VLDoF "to water" and "to sign" were combined with the nouns "the flowerbed" (word pair of type 1 − VLDoF + Non-graspable object Noun) and "the cheque" (word pair of type 2 − VLDoF + Graspable object Noun) respectively, and the VHDoF "to book" and "to recycle" were combined with the nouns "the medical" (word pair of type 3 − VHDoF + Non-graspable object Noun) and "the bottle" (word pair of type 4 − VHDoF + Graspable object Noun), respectively. In order to select word pairs matched for lexical frequency, an independent group of 16 students evaluated a set of 64 pairs on a ten-point scale with respect to their lexical frequency in written Italian. We selected a total of 48 word pairs with similar ratings in estimated lexical frequency. Mean estimated lexical frequency scores for word pairs of type 1, 2, 3 and 4 were 6.56, 6.54, 6.73 and 6.31, respectively. A one-way analysis of variance (ANOVA) with four levels, one for each word pair type, showed no reliable difference ($F[3, 44] = .378$, $p = .77$). No reliable difference among the four types of word pairs was found also for the lexical frequency estimated by using Google, the most-used search engine on the Web, ($F[3, 44] = 1.405$, $p = .25$), and by summing the individual lexical frequency of the linguistic constituents of each word pair of CoLFIS (Corpus and Frequency Lexicon of written Italian, Laudanna et al. (1995); $F[3, 44] = 1.362$, $p = .27$).

Furthermore, the four pair types were matched for word length (averaged values: 17.83, 18.92, 18.92, and 19.25 letters for word pairs of type 1, 2, 3 and 4, respectively).

In addition to the 48 critical word pairs, 48 filler pairs were constructed. Action verbs that were combined with nouns referring to non-graspable objects in the critical word pairs, were combined with nouns referring to graspable objects in the filler pairs so as to form sentences which did not make sense, and *vice versa* for the other action verbs. For example, the VLDoF "to water" and "to sign" were combined with the nouns "the handle" and "the vortex", respectively. Critical and filler verb–noun pairs were matched for word length.

2.3. Procedure

The experiment was carried out in a sound-attenuated room, dimly illuminated by a halogen lamp directed toward the ceiling. Participants sat comfortably in front of a computer screen with their chins supported by a chin rest in order to maintain a stable head position and keep their eyes at a constant distance (57 cm) from the screen.

Each trial started with a fixation cross at the center of the screen. After a variable delay of 500–1000 msec, a verb–noun pair was presented. The word pair was displayed at the center of the screen and written in white lowercase Courier New bold font (point size = 18) on a black background. Participants were randomly assigned to one of two groups and tested individually. Participants in the first group were asked to press the "p" key on the keyboard with their right index finger if the word pair made sense and the "q" key with their left index finger if the word pair did not make sense; participants in the other group were required to do the opposite. The keyboard was positioned in front of participants so as the response keys were positioned symmetrically with respect to their body midline. The word pair remained visible until the response was given. Participants were informed that their response times would be recorded and invited to respond as quickly as possible while still maintaining accuracy. Participants received visual feedback after pressing the incorrect key

("ERROR"), as well as after pressing a key prior to the word pair onset ("ANTICIPATION") or after taking 2 sec to respond ("YOU HAVE NOT ANSWERED"). The inter-trial interval was 1 sec. During this period the PC screen remained blank. The 96-word pair stimuli were presented twice in random order. The experimental trials were preceded by 24 training trials. Throughout the experiment, participants could take a break, if needed, after every 48 trials. Thus, in the experimental session, which lasted about 20 min, each participant was presented with 192 trials (12 word pairs × 2 verb type × 2 noun type × 2 pair sensibility × 2 replications) plus 24 practice trials, for a total of 216 trials.

3. Results

Two participants were removed from the analysis because their error rate exceeded 15%. Trials with errors (anticipations, missing and incorrect responses) were discarded without replacement (7.3% of total trials). A preliminary analysis on errors showed that there was no speed-for-accuracy tradeoff. Response times (RTs) were screened for outliers before being analyzed: RTs two standard deviations higher or lower than the participant mean were removed (4.4% of experimental trials). The remaining RTs were entered in two 2 Sensibility (sensible *vs* non-sensible word pair) × 2 Mapping (yes-right/no-left *vs* yes-left/no-right) mixed ANOVAs. The first ANOVA was conducted with participants as random factor whereas the second ANOVA was conducted with items as random factor. In the analysis on participants, Sensibility was manipulated as a within-subjects factor and Mapping as a between-subject factor. Due to our experimental design, in the analysis on item, the factor Mapping turned into the factor Response Hand (right *vs* left). In this analysis Response Hand was manipulated as a within-items factor with Sensibility as a between-items factor. Analyses denoted F^1 were conducted with participants as random factor and analyses denoted F^2 were conducted with item as random factor in the design [for analyses with participants and items as random factors see Clark (1973) and Coleman (1964)]. When necessary post-hoc analyses were carried out using the Newman–Keuls test.

Participants responded 84 msec more quickly to sensible than to non-sensible verb–noun pairs ($F^1[1, 20] = 126.92$, $MSe = 78409$, $p < .0001$; $F^2[1, 94] = 36.62$, $MSe = 288742$, $p < .0001$). More interestingly, responses were faster when participants had to respond to non-sensible sentences with their right hand (mean RT = 1136 msec) than with their left hand (mean RT = 1176 msec), as clearly indicated by the significance of the interaction between Sensibility and Mapping ($F^1[1, 20] = 6.8$, $MSe = 4202$, $p < .05$), in the analysis on participants, and between Sensibility and Response Hand in the analysis on items ($F^2[1, 94] = 23.07$, $MSe = 28897$, $p < .0001$, see Fig. 1).

Further analyses were performed considering sensible and non-sensible word pairs, separately.

3.1. Sensible word pairs

Two 3-way mixed ANOVAs, one with participants and the other with items as random factors, were performed. The independent variables were Response Hand (right *vs* left), Verb Type (VLDoF *vs* VHDoF) and Noun Type (Graspable *vs* Non-graspable objects). In the analysis on participants, Response Hand was manipulated as a between-subjects factor whereas Verb Type and Noun Type as within-subjects factors. In the analysis on items, Response Hand was manipulated as a within-items factor whereas Verb Type and Noun Type as between-items factors. Word pairs containing a VLDoF were processed 46 msec more quickly than pairs containing VHDoF ($F^1[1, 20] = 49.09$, $MSe = 46063$, $p < .0001$; $F^2[1, 44] = 5.05$, $MSe = 49360$, $p < .05$). Furthermore, the participants were 34 msec faster to respond to word pairs containing a VHDoF combined with a noun referring to a non-graspable object than to a graspable object ($F^1[1, 20] = 6.16$, $MSe = 5145$, $p < .05$, see Fig. 2 Top). Although both the analyses on participants and items showed the same pattern of results, the Verb Type × Noun Type interaction was significant only in the analysis on participants.

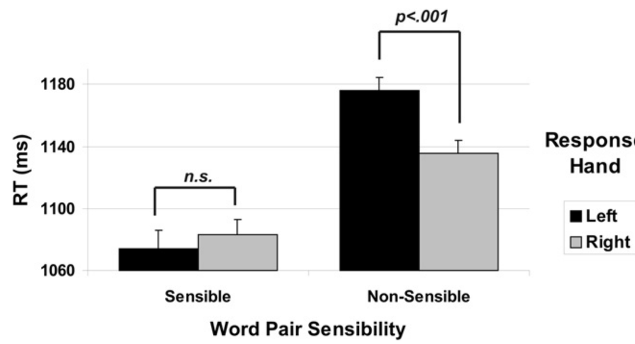

Fig. 1 – Mean RTs as a function of Word Pair Sensibility separately for each hand used to give the response (black bars represent the left hand whereas light gray bars the right hand). Error bars represent the standard errors. *p* Values above the square brackets indicate the significance values revealed by post-hoc analyses carried out using the Newman–Keuls test.

3.2. Non-sensible word pairs

Two ANOVAs, one with participants and the other with items as random factors, were performed on RTs measured for non-sensible sentences, with the same independent variables as those described in the sensible word pairs results subsection. Word pairs containing a VLDoF were processed 16 msec more quickly than word pairs containing VHDoF ($F^1[1, 20] = 4.81$, $MSe = 5694$, $p < .05$; the same tendency was revealed by the item analysis although the effect was not significant). As already revealed by the Sensibility × Mapping analyses (see above), right hand responses were 40 msec faster than left-hand responses ($F^2[1, 44] = 36.96$, $MSe = 38309$, $p < .001$). Although this main effect was significant only for the analysis on item, both the analyses on participants and items showed a significant interaction between Hand of Response and Noun Type ($F^1[1, 20] = 4.31$, $MSe = 5139$, $p = .05$; $F^2[1, 44] = 4.61$, $MSe = 4768$, $p < .05$), indicating that the hand difference was more pronounced for word pairs containing a noun of a graspable object (54 msec) as compared to word pairs containing a noun of a non-graspable objects (26 msec, see Fig. 2 Bottom).

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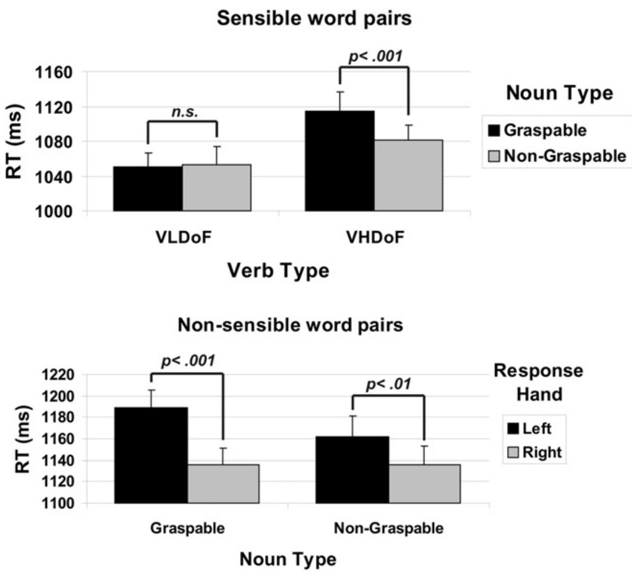

Fig. 2 – Top: mean RTs, measured for the sensible word pairs, as a function of Verb Type separately for each Noun Type (black bars represent nouns referring to graspable objects whereas light gray bars nouns referring to non-graspable objects). Bottom: mean RTs, measured for the non-sensible word pairs, as a function of Noun Type separately for each Response Hand (black bars represent the left hand whereas light gray bars the right hand). In both graphs, error bars represent the standard errors. *p* Values above the square brackets indicate the significance values revealed by post-hoc analyses carried out using the Newman–Keuls test.

4. Discussion

The problem concerning the extent to which sensorimotor simulation entailed during word meaning retrieval is situated, is currently a matter of debate within the theoretical framework of embodied language (e.g., Fischer and Zwaan, 2008). This problem is particularly relevant since language, as compared to vision, represents situations, conceived as sets of agents, objects, events and mental states, in a non-analog manner (Buccino et al., 2005). As a consequence, what can be detected with just a single glance cannot be expressed by a word, but rather by a series of words or even a series of sentences.

In general, language efficiency in describing situations strictly depends on sensorimotor specificity of the words used. For example, words such as “animal”, “dog”, “chiwawa”, and the name of one’s own dog carry more and more sensorimotor specificity relative to a particular dog. In keeping with the embodied view on language understanding, a more situated and less time-consuming simulation should be entailed during the understanding of the words used in the example.

To investigate the effect of word sensorimotor specificity on situating the simulation process during language understanding, sensible and non-sensible sentences, which consisted of a verb referring to a concrete action with low or high DoF combined with a noun denoting a graspable or non-graspable object, were used in a sensibility judgment task. The resulting different types of sentences were matched for lexical frequency and word length (see Materials section). Linguistic material used in the present study allowed us to investigate not only whether the amount of sensorimotor specificity of words plays a role in modulating the motor system during language understanding, but also to disentangle the relative role of verbs and nouns in situating the simulation and to explore its nature, if any, during comprehension of sentences that do not make sense.

In keeping with our predictions, we found that sensible sentences containing a VLDoF were processed 46 msec faster than sentences containing a VHDoF. The main effect of Verb Type reasonably indicates that verbs expressing an action with low DoF are more effective than verbs expressing an action with high DoF to situate the simulation process during language understanding, with the result of shortening the time needed to comprehend the meaning of the sentence and, thus, to judge its sensibility. More interestingly, response time in judging sensible sentences containing a VLDoF was not affected by the amount of sensorimotor specificity of nouns, which exerted an effect only when sentences contained a VHDoF: specifically, responses were 34 msec faster when a VHDoF was followed by a noun denoting a non-graspable than a graspable object.

The lack of an effect of noun type on judging the sensibility of VLDoF sentences replicates the findings discussed by Zwaan and Taylor (2006) who found, using sentences with verbs expressing specific behavioral events (here termed as VLDoF), that the simulation process does not extend beyond the action verb to the linguistic constituents that code acted-upon objects. Rather than being the outcome of a shift of attention from the action itself, as proposed in the LFH (Taylor and Zwaan, 2008), we suggest that this result is consistent with the idea that during the understanding of VLDoF, one simulates a specific action aimed at a limited set of objects that anticipates the interaction with the object denoted by the following noun. The soundness of our explanation is strengthened by the result that the amount of sensorimotor specificity expressed by nouns affects time needed to respond to sensible sentences containing a VHDoF. With these kinds of verbs, which express an action that can be performed in very many ways, the relation between the action and the acted-upon object cannot be plausibly anticipated by the simulation entailed during the understanding of the verb, but it is constructed only during the understanding of the following noun, causing an increase of response times.

The finding that much more time was required to judge the sensibility of a sentence containing VHDoF associated with nouns denoting graspable than non-graspable objects runs parallel with those of previous studies (e.g., Buccino et al., 2005; Sato et al., 2008), indicating that during the comprehension of language material related to action there is a specific simulation entailing the effector implied in the linguistic form. In particular, a decrease in speed of performance was observed when the response was given with the effector (hand or foot) expressed in the linguistic material, indicating that simulation engaged in language understanding involves the same kind of motor representations that are also used for planning and executing the response. In our study, the result that, after processing a VHDoF, responses to sensible sentences containing a noun of a graspable object were slowed down relative to sentences containing a noun of a non-graspable object is consistent with an explanation in terms of a competition of resources for planning the hand movement needed to give the response and for simulating a specific action, among those possible, that is selected by the noun.

To sum up, the experimental results with sensible sentences can be accounted for by a different time course for understanding action verbs with low or high DoF. The comprehension of VLDoF seems to imply a simulation that is sensitive not only to the action but also to a specific set of objects and that finishes before the processing of noun. Thus, the simulation of noun appears to be faster or not necessary to comprehend the sensibility of the sentence. As a consequence, there is a lack of competition of common resources for language understanding and response planning. In contrast, the comprehension of VHDoF seems to imply the simulation of a less specific action that is not aimed at a restricted set of objects. This simulation appears to last till the processing of noun, determining a competition of resources for language understanding and response planning.

A further finding of our study was that the time needed to respond was slower for non-sensible sentences as compared with sensible sentences, as already found in previous works (e.g., Borghi and Scorolli, 2009). This result can be plausibly explained not only by the little familiarity with non-sensible sentences, as they describe unfeasible or illogical behavioral events, but also by the fact that "no" responses are slower than "yes" responses, as research in cognitive psychology frequently points out. These two accounts cannot explain, however, the additional result that non-sensible sentences containing a VLDoF were processed 16 msec faster relative to non-sensible sentences containing a VHDoF. This difference in time processing, rather suggests that a simulation is entailed also during the comprehension of sentences expressing unfeasible or illogical behavioral events. The lack of an interaction between verb and noun type seems to indicate a mutual independence between the simulation evoked by the verb and the noun. Moreover, the left-hand disadvantage, which was particularly marked when the sentence contained a noun of a graspable object, is consistent with the idea of a simulation process that selectively activates motor programs related to the interaction of the right hand with the objects described by the noun. The possibility that processing nouns of graspable objects, such as tools and fruits, automatically activates hand motor programs related to object grasping has already been demonstrated by a series of behavioral and neuroimaging studies (e.g., Grafton et al., 1997; Chao and Martin, 2000; Gerlach et al., 2002; Glover et al., 2004; Tucker and Ellis, 2004).

Our explanation in terms of an independence among simulations entailed by understanding linguistic constituents of sentences that did not make sense seems also to be corroborated by the finding that, in contrast with non-sensible sentences, response hand had no effect on time needed to process sensible sentences. This lack of hand effect can be likely interpreted by assuming that the simulation of the action expressed by the verb, which in our study referred to a bimanual action, does not remain separated but is integrated with the simulation of the object denoted by the noun, determining an activation of motor programs of both hands related to object manipulation, rather than motor programs of the preferred hand related to object grasping.

The proposal here, concerning the nature of simulation process during understanding sentence that does not make sense, is consistent with the conclusion drawn by Buccino et al. (2005): simulation is not engaged in processing the meaning of behaviors that are not part and cannot be part of human sensorimotor repertoire. Nonetheless, simulation seems to be involved in the understanding of those portions of meaningless behavioral events that belong or can belong to the human sensorimotor repertoire. This last suggestion represents an alternative to that made by Costantini et al. (2005) according to which simulation of biologically impossible movements can be achieved through a generalization of the simulation of similar biologically possible movements.

The novelty of the present study is that the amount of sensorimotor specificity expressed by linguistic constituents of sentences significantly affects the simulation process entailed in language understanding. Furthermore, we were able to ascertain the relative weight of verb and noun sensorimotor specificity in situating the simulation process. The simulation of the action expressed by a verb referring to an action with low DoF drags behind the simulation of a class of objects on which the action can be performed. The sensorimotor specificity of a noun acts to situate the simulation process by selecting the particular action among all those that are expressed by a verb expressing a behavior with a high DoF. Finally, we demonstrated that simulation is also active during the understanding of sentences that describe unfeasible or illogical behavioral events. In this case, simulations of referents denoted by the verb and the noun remain mutually independent. Overall, our findings are in line with the theoretical framework of embodied language and have relevant implications for physiological and neural models concerning the relationships between language and the sensorimotor system.

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