Language comprehension and dominant hand motion simulation

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Abstract

In five experiments participants were presented with pairs of nouns and verbs. They were asked to decide whether the combinations made sense or not. Half of the participants responded “yes” with the dominant hand, half with the left hand. When pairs referred to manual and mouth actions, participants responded faster with the dominant than with the left hand with sensible sentences. When pairs referred to manual and foot actions the result was opposite. Results suggest that language processing activates an action simulation that is sensitive both to the effector involved and to the goal expressed by the sentence.

Keywords: language comprehension – motor system – simulation – embodiment – motor resonance.

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The experiments have been carried out according to APA ethical guidelines for research with human subjects.

Language Comprehension and Dominant Hand Motion Simulation

INTRODUCTION

Concepts are the minimal units of our knowledge, a sort of "mental glue" linking our past experiences with our current interaction with the world (Murphy, 2002). This paper will focus on object concepts mediated by words, and particularly on the relationship between words and action. In contrast with the view that concepts are generated by arbitrary and amodal symbols (Landauer & Dumais, 1997), the embodied view suggests that concepts are grounded in sensorimotor processes (Barsalou, 1999; Gallese & Lakoff, 2005; for a review on object concepts and action see Borghi, 2005). Concepts are not amodal but multimodal, and conceptual information is distributed over modality specific domains (Barsalou, Simmons, Barbey, & Wilson, 2003; Boronat, Buxbaum, Coslett, Tang, Saffran, Kimberg, & Detre, 2005; Gallese & Lakoff, 2005; Martin, Wiggs, Ungerleider, & Haxby, 1996). Thus, according to the embodied theory, thinking of a telephone leads to the activation of auditory, visual, and tactile information – the sound of the telephone ringing, the color of the receiver, the smoothness of its surface etc. In other words, thinking about an object leads to a re-experiencing (simulation) of the interaction with the object (Barsalou, 1999; Barsalou et al., 2003). Simulations consist of reenactments of our sensorimotor experiences with objects and entities. Significantly, these experiences are both perceptual and motor. It has been shown that a subset of the same neurons fire for sensory modalities like vision, hearing, touch, and are integrated with motor information (for a review, see Fogassi & Gallese, 2004).

Accordingly, the neural areas recruited when we think about an object or about an entity and prepare to act are the same that are recruited when we perceive and interact with its referent. The multimodality of object concepts and the centrality of action information in their construction is demonstrated in a variety of experiments showing that visual stimuli activate motor information. Even with tasks that are intended as unimodal, the multimodality of concepts emerges (Smith, 2005). For example, Tucker and Ellis (2001) asked participants to evaluate whether different-sized objects are artifact or natural kinds by mimicking a precision or a power grasp. They found a congruency effect between the object size and the kind of grip used to respond, even if the object size was not relevant to the task.

According to the embodied view, words mediating concepts also enhance the neural pathways involved in perceiving objects and interacting with them: thus, the word “telephone” would re-enhance the experiences of past interactions with telephones. Substantial evidence from fields ranging from psychology to neuroscience to cognitive linguistics (for reviews see Bergen, 2005; Gibbs, 2003; Pecher & Zwaan, 2005) provides support for this embodied view of linguistic meaning. The indexical hypothesis put forth by Glenberg and Robertson (2000) explains in an embodied perspective the nature of the relationships between words and their referents. According to this hypothesis, words are linked to objects in the world, their referents, or to analogical representations such as pictures or perceptual symbols (Barsalou, 1999). For example, the word “handle” refers to its referent, a handle, or to an analogical representation of the handle. Therefore, words that refer to objects would evoke first of all perceptual information relative to such objects. Given the close relationship between perceptual and motor processes, words should also evoke motor information. Depending on their perceptual features, in fact, objects can activate affordances (Gibson, 1979). For instance, different kinds of handles may afford different actions: some must be turned, others are pushed upon as when opening a door, etc.

When applied to words and sentence comprehension, the simulation theory holds that language comprehension entails a mental simulation of the situation or action described by the sentence (Zwaan, 2004). The neural substrate for the idea of simulation resides in the phenomenon of motor resonance. Recent neurophysiological studies have produced important discoveries regarding the macaque monkey's premotor cortex (area F5). Practically speaking, this area contains a vocabulary of "motor acts" (Gentilucci, 2003). Unlike F1 neurons, which encode different kinds of movements, F5 neurons refer to goal-directed actions. Some neurons are sensitive to a general action category (hold, grasp, tear etc), others to the way an object can be grasped (e.g., precision vs. whole hand grasp). Further neurons are concerned with the temporal segmentations of actions (e.g., hand opening, closing, holding etc.) (Fadiga, Fogassi, Gallese, & Rizzolatti, 2000). Recent studies have shown that many F5 neurons respond to actions performed with different effectors, provided that they share a common goal, for example discharging when reaching for an object with the left hand, the right hand or with the mouth. The F5 area contains two varieties of visuomotor neurons: canonical and "mirror" (Di Pellegrino, Fadiga, Fogassi, Gallese & Rizzolatti, 1992; for a recent review see Rizzolatti & Craighero, 2004). Canonical neurons discharge when macaques see graspable objects and when they execute specific actions (for example, when they grasp an object with a precision or with a power grip), while mirror neurons fire when the monkey performs an action or when it observes another monkey or an experimenter performing a goal-directed action, such as, for example, grasping an object. Importantly, they do not discharge when the object alone is presented. Recently it has been proposed that these neurons may help explain various cognitive phenomena such as empathy, mind reading abilities and conceptual organization (Gallese & Goldman, 1998; Gallese & Lakoff, 2005).

Of particular relevance in relation to our aim is the fact that recent studies suggest that the homologue of the F5 area in humans is Broca’s area, and it has been proposed that mirror neurons may play a role in language evolution (Rizzolatti & Arbib, 1998). Broca’s area was considered to be devoted to speech production. Recently, however, it has been shown that a motor representation of hand actions is present in this area. In addition, Buccino, Binkofski, Fink, Fadiga, Fogassi, Gallese, Seitz, Zilles, Rizzolatti, & Freund (2001) found that different regions of the premotor cortex and Broca’s area are activated depending on the effector involved in their fMRI study that required participants to observe videos of actions involving the mouth, the hand and the foot. Other brain imaging and behavioral studies provide evidence, consistent with these findings, that cortical areas are organized in a somatotopic way. For example, Pulvermüller, Härle and Hummel (2001) found topographical difference in the brain activity patterns generated by verbs referring to actions performed with the legs, the face, and the arms starting from 250 ms after word presentation. Other recent evidence suggests that the simulations activated while processing a sentence are quite detailed. Buccino, Riggio, Melli, Binkofski, Gallese and Rizzolatti (2005) showed that simulations run while processing action sentences are sensitive to the kind of effector required to perform the action. In Buccino et al.'s study, participants had to listen to sentences of three kinds: abstract sentences, sentences describing actions performed with hands, and sentences describing actions performed with feet. The task required participants to respond with the hand or foot, for concrete sentences, and to avoid responding for abstract sentences. The results showed that sentences can prime the motor system in an effector specific way.

Our experiments sought to test whether the simulations running while processing pairs of verbs and nouns (sentences) are detailed enough to be sensitive to the difference between the dominant and the non-dominant hand. It is well known that right-handed individuals are more dexterous to perform skilled actions with their right hand. This could lead to a general advantage in response times with right hand responses. However, we predict an advantage of right hand responses only during the comprehension of words that refer to sensible actions. Namely, as we typically use the dominant hand to perform skilled actions with objects (e.g., writing with a pen), one might expect that if while reading a verb-noun combination we form a mental simulation of such an action, we would activate more the dominant (right) than the non-dominant hand. This advantage of the dominant hand should not occur when the simulation we run is not coherent, that is, when the verb-noun combination is meaningless. Thus, in a sentence sensibility task we predict faster responses of the dominant hand compared with the non-dominant one in the case of sensible combinations, whereas in the case of combinations that did not make sense we do not predict any advantage of the dominant hand. If we found an advantage of the dominant hand for sensible combinations referring to hand action, this would suggest that the simulations formed while reading sentences (or, more precisely, by reading verb-noun pairs) are very detailed, that is, that they are not only determined by the kind of effector (e.g., hand vs. foot), but also by the specific effector (e.g., right vs. left hand). But what becomes of the advantage of the dominant hand when we process sensible combinations referring to mouth actions (e.g., bite an apple) or to foot actions (e.g., kick a ball)? In Experiment 2 and 3, sentences involving a hand movement and sentences involving the mouth or a foot movement were compared. If the simulation formed is sensitive to the effector alone, then we should not find the advantage of the dominant hand in the case of pairs that refer to mouth and foot movements. However, if the sensitivity to the effector involved is modulated by the goal expressed in the sentence, as the literature on mirror neurons and on motor resonance suggests, then we should find an advantage of the dominant hand with mouth actions as well, but not with foot actions. This is because eating something typically implies bringing it to the mouth with the hand while performing an action with the foot does not imply a prior hand action.

EXPERIMENT 1.a

The aim of Experiment 1.a was to test whether or not an internal simulation of the action described is activated during comprehension of a verb-noun combination describing a hand action with an object. Participants were presented with verbs followed by nouns; their task consisted in pressing a different key in order to decide whether the combination verb-noun was sensible or not (e.g., to paint – the picture vs. to melt – the chair). All verb-noun pairs that made sense referred to hand actions with objects. Participants were randomly assigned to two different groups; half of them were required to respond "Yes, it makes sense" with the dominant hand and "No, it doesn't make sense" with the left hand; the other half were asked to do the opposite.

If comprehending a sentence entails a simulation of the described action, then reaction times (RTs) with sensible sentences should be faster with the dominant hand than with the left hand. Such an advantage of the dominant hand should not appear in the case of combinations that didn't make sense.

Method

Participants

Fourteen volunteers took part in the experiment. They were all students of the University of Bologna, native Italian speakers and right-handed according to the Edinburgh Handedness Questionnaire (Oldfield, 1971).

Materials

Materials consisted of word pairs composed of a verb and a noun. We constructed 48 critical pairs composed of a verb followed by a concept noun. 24 concept nouns designating common objects, for example, toothbrush, pencil, shoe, spoon, and hammer were chosen. Half of the objects are typically manipulated with the dominant hand; the other half requires bimanual manipulation. In addition, for each object we selected one verb referring to a skilled action to perform with the dominant hand, and another verb referring to an action not necessarily performed with the dominant hand.

Each concept noun could be paired with one of 2 verbs (e.g. spoon – to eat; spoon – to dry). Of the 2 critical verbs, one designated an action which could be performed with both hands, another referred to an action to be performed with the dominant hand. For example, the object “picture” was paired with the action “to paint” and with the action “to take off”, the object “spoon” with the action “to eat” and “to dry”. Consider that typically the first kind of action referred to an object’s function; for this reason it typically requires a skilled behavior to be performed with the dominant hand. For example, the action of “hammering” (in Italian it is expressed through a verb and a noun, “battere con il martello”) requires more skills than the simple action of “lifting a hammer”. In order to select the materials, an independent group of 16 participants evaluated a set of 56 sentences on a 7 point scale according to the degree of necessity to use the dominant hand to perform the described action with the object. We chose the 48 pairs with a higher difference between the degree of dominance of the two actions performed with the same object: for example, “to paint a picture” was selected as a Right Dominant action, “to take off a picture” as a Not-Right Dominant one. From now on the pairs implying a Right Dominant hand action will be called Right-Dominant, the pairs that do not imply a right dominant action will be named Not-Right-Dominant.

In addition to the 48 critical pairs, 48 filler pairs were constructed. In these pairs, each of the 24 concept noun was combined with 2 verbs leading to sentences which didn't make sense. So, each concept noun appeared 4 times, twice in a critical pair and twice in a filler pair.

The materials of all the experiments can be found at the following links: http://laral.istc.cnr.it/borghi/BS-Exp1a.htm, http://laral.istc.cnr.it/borghi/BS-Exp1b.htm, http://laral.istc.cnr.it/borghi/BS-Exp2.htm, http://laral.istc.cnr.it/borghi/BS-Exp3.htm..

Procedure

Participants were randomly assigned to one of two groups. Participants in both groups were tested individually in a quiet laboratory room. They sat in front of a computer screen and were instructed to look at a fixation cross that remained on the screen for 1000 ms. Then a verb appeared on the screen. After 600 ms the verb was substituted by a concept noun. The timer started operating when the concept noun appeared on the screen. For each verb-noun pair, participants were instructed to press a key if the combination made sense, and to press another key if the combination did not make sense.

Participants in the first group were asked to respond "yes" with their left hand and "no" with their right hand; participants in the other group were required to do the opposite. All participants were informed that their response times would be recorded and invited to respond as quickly as possible while still maintaining accuracy. Stimuli were presented in a random order. The 96 experimental trials were preceded by 12 training trials.

Results

One participants' data were removed as their responses included errors over 15%. All incorrect responses were eliminated. As the error analysis revealed that there was no speed-for-accuracy tradeoff, we focused on the RT analysis. To screen for outliers, scores 2 standard deviations higher or lower than the mean participant score were removed for each participant. Removed outliers accounted for 3.6% of response trials.

The remaining response times were submitted to a 2 (Sensibility: Sensible vs. Non-Sensible verb-noun pairs) X 2 (Mapping: yes-right / no-left vs. yes-left / no-right) mixed factor ANOVA with Mapping as a between participants variable. Due to our experimental design, in the analysis conducted with items as random factor, the factor Mapping turned into the factor Response Hand (Right vs. Left). In the analysis on items Response Hand was manipulated within items, while Sensibility was manipulated between items. Analyses denoted F^1 were conducted with participants as a random factor; analyses denoted F^2 with items as a random factor in the design (for analyses with participants and items as random factors, see Clark, 1973; Coleman, 1964).

Participants responded 50 ms more quickly to Sensible than to Non-Sensible sentences, F^1 (1,11) = 6.71, *MSe* = 2405.21, $p<.05$; F^2 (1, 62) = 10.36, *MSe* = 6830.29, $p<.005$. Most interestingly, responses were quicker when participants had to respond to sensible sentences with the right hand (*M* = 572.98 ms) than with the left hand (*M* = 711.63 ms), as clearly indicated by the main effect of Mapping, F^1 (1,11) = 6.74, *MSe* = 18425.54, $p<.05$, in the analysis on participants. In fact in this kind of analysis the variable Response Hand is not considered per se, as it is embedded in the Mapping factor. In the items analysis, the same outcome is showed by the significant effect of Response Hand, F^2 (1,62) = 3.25, *MSe* = 15222.55, $p=.07$ and by the interaction between

Sensibility and Response Hand, F^2 (1, 62) = 121.74, *MSe* = 4681.91, *p*<.0000001 (see Figure 1 top). The data suggest that left-hand responses were faster for non-sensible than for sensible sentences. This result was unexpected. However, we can tentatively explain the advantage of the left hand with non-sensible sentences as a direct consequence of some sort of inhibition mechanism. In other words, it is possible that, given that non-sensible sentences activated an incoherent simulation, participants “blocked” their right hand, and this produced as outcome faster responses with the left hand.

Further analyses were performed considering only the Sensible sentences. Response times were submitted to a 2 (Response Hand: Right vs. Left) X 2 (Verb Dominancy: Right-Dominant vs. Not-Right-Dominant action) mixed factor ANOVA, with Response Hand as a between participants variable. In the analysis conducted with items as random factor both Response Hand (Right vs. Left) and Verb Dominance were manipulated within items. Right Hand responses were 111 ms faster than Left Hand responses, F^1 (1, 11) = 4.06, *MSe* = 79380.84, *p*<.07; the effect was found also in the analysis on items, F^2 (1, 23) = 41.72, *MSe* = 5301.87, *p* < .00001. Right-Dominant verb-noun pairs were processed 78 ms faster than Not-Right-Dominant pairs, F^1 (1, 11) = 21.19, *MSe* = 1866.20, *p*<.001; the effect was significant also in the items analysis F^2 (1, 23) = 23.22, *MSe* = 5723.06, *p* < . 0001. The interaction between Verb Dominancy and Response Hand was significant only in the items analysis, F^2 (1, 23) = 5.48, *MSe* = 2789.60, *p* < .05. Both the analysis on participants and items showed the same pattern: participants were faster with Right-Dominant verb-noun pairs than with Left Dominant ones both with the Right and the Left Hand. This pattern suggests that verbs referring to skilled actions activate more strongly both effectors in comparison to verbs referring to more general actions.

Insert Figure 1 about here

In order to be sure that the results were not a result of familiarity, an independent group of 16 participants was asked to evaluate sensible sentence familiarity on a 7 point scale. The correlation between the RTs and the familiarity ratings were quite low (r = -0.29), which led us to exclude the possibility that our results were due to familiarity of the verb-noun combinations.

EXPERIMENT 1.b

A control experiment was performed, in order to verify whether the advantage of the dominant hand we found in Experiment 1.a was specific to action sentences or whether it was simply due to a semantic compatibility between right hand responses and sensible sentences. If the results found in Experiment 1.a are due to semantic compatibility, then we should find the advantage of the dominant hand with sensible sentences also with sensible sentences that do not refer to action. Such an advantage of the dominant hand should not appear in the case of sentences that don’t make sense.

Method

Participants

Fifteen students of the University of Bologna took part in the experiment. They were selected with the same criteria used for Experiment 1.a.

Materials

Materials consisted of word pairs composed of a verb and a noun, as in Experiment 1.a. We constructed 48 critical pairs composed of a verb followed by a concept noun. None of the concept nouns referred to graspable objects, and the selected verbs did not refer to body actions. Some examples of the pairs are: “to think-solution”, “to memorize-event”, “to evaluate-color”, “to respect-rule”. In addition to the 48 critical pairs, the same 48 filler pairs used in Experiment 1.a were utilized.

Procedure

The procedure was exactly the same as in Experiment 1.a.

Results

All incorrect responses were eliminated. No speed-for-accuracy tradeoff was present, so we will discuss the RT analysis. The same trimming method of Experiment 1.a was used. Removed outliers accounted for 3.9 % of response trials. Two ANOVAs, one with participants and another with items as random factor, were performed, with the same factors of Experiment 1.a. Participants responded 33.15 ms more slowly to Sensible than to Non-Sensible sentences, F^1 (1,13) = 12.16, *MSe* = 674.89, $p < .005$; the effect was significant also in the items analysis, F^2 (1, 92) = 7.67, *MSe* = 6456.06, $p < .01$, and is probably due to the complexity of abstract noun-verb combinations. More importantly to our aim, neither the main effect of Mapping - in the analysis on participants, F^1 (1,13) = .00, *MSe* = 50408.22, $p = .99$, nor the effect of Response Hand in the items analysis, F^2 (1,92) = 0.10, *MSe* = 4522.33, $p = .75$, nor the interaction between Sensibility and Response Hand in the items analysis reached significance, F^2 (1,92) = 0.00, *MSe* = 4522.33, $p = .98$.

Discussion

The results are in line with the simulation hypothesis. As predicted, the results of Experiment 1.a showed that the dominant hand was activated by reading verb-noun pairs describing manual actions. Crucially, the advantage of the dominant hand concerned only the pairs describing actions that can actually be committed with the objects in question. The results of Experiment 1.b confirm that the dominant hand advantage is not due to a simple semantic compatibility between right-hand responses and sensible sentences. Bekkering, Wohlschläger and Gattis (2000) obtained similar results in an action imitation experiment which demonstrated that children use their dominant hand more frequently during grasping than during other kinds of manual actions, such as pointing.

Further support to the simulation hypothesis was given by the advantage of Right-Dominant compared to Not-Right-Dominant actions, even though there was no evidence of a specific advantage of the dominant hand with right-dominant actions. Rather, it seemed that all skilled manual actions implying an interaction with objects, as the ones used, pre-activated both hands.

EXPERIMENT 2

The advantage of the dominant hand found in Experiment 1 provides support for the simulation theory. Experiment 2 was designed in order to verify whether the effector referred to by the sentence might influence response times. For this reason, we used both foot and manual verbs that can be followed by the same noun (e.g., kick vs. throw the ball). As in Experiment 1, participants were instructed to indicate their decision by pressing a different key to show whether the verb-noun combinations made sense or not. As mentioned in the introduction, previous evidence (Pulvermüller et al., 2001; Pulvermüller, 2003) suggests that different cortical areas are activated while hearing sentences referring to different effectors. Behavioral evidence on the differential role of manual and foot actions has also been provided (Buccino et al., 2005). However, it has not yet been demonstrated whether responding with the right or with the left hand is sensitive to the fact that actions referred to by the sentences are performed with different effectors. If, while reading and comprehending the meaning of a sentence, participants are sensitive to the effector implied by the verb, no evidence of an advantage of the dominant hand with sensible foot-sentences should be found. More specifically, we predicted that, in the analysis performed only on sensible sentences, responses with the right hand should be faster with hand actions than with foot actions.

Method

Participants

Twenty-two volunteers took part in the experiment. They were selected according to the same criteria used in Experiment 1.

Materials

As in the previous experiment, stimuli consisted of pairs composed of a verb and a noun. We selected 24 object concept-nouns that could be preceded either by a verb indicating a manual action (e.g., to throw – the ball; to pick up – the grapes; to throw – the sandal; to rip – the grass) or by a verb referring to an action to perform with the foot (e.g., to kick – the ball; to press – the grapes; to wear – the sandal; to step on – the grass). We chose a further 48 verb-noun pairs that referred to actions which do not make sense.

Procedure

Participants were divided into two groups. Half of them were asked to respond “yes” with their left hand and “no” with the right hand; the other half was asked to do the opposite. The procedure was exactly the same as in Experiment 1.

Results

All incorrect responses were eliminated. As in Experiment 1, there was no evidence of a speed-accuracy tradeoff. To screen for outliers, we used the same criterion as in the previous experiment. Removed outliers accounted for 3.4% of response trials. The remaining response times were submitted to a 2 (Sensibility: Sensible vs. Non-Sensible verb-noun combination) X 2 (Mapping: yes-right / no-left vs. yes-left / no-right) mixed factor ANOVA with Mapping as a between participants variable. In the analysis conducted with items as random factor, Sensibility was manipulated between items, whereas Response Hand was manipulated within items. Participants responded 33 ms more quickly to Sensible than to Non-Sensible sentences, F^1 (1,20) = 6.11, *MSe* = 1998.57, $p<.05$; however, the effect was not significant in the items analysis. Crucially participants were slower (*M* = 863.51 ms) when they had to respond to sensible sentences with the Right Hand rather than with the Left one (*M* = 701.73 ms), as indicated by both the Mapping factor in the analysis on participants, F^1 (1,20) = 4.13, *MSe* = 69086.66, *p* =. 055, and the interaction between Sensibility and Response Hand in the items analysis, F^2 (1, 46) = 81.31, *MSe* = 7307.51, $p<.0000001$ (see Figure 1 middle). The effect was opposite to the effect found in the Experiment 1.a, as responses with the right hand were inhibited. There seems to be an interference leading to slower RTs with the right hand. Newman-Keuls post-hoc analysis indicates that the fastest responses were obtained in responses triggered by Sensible sentences with the left hand and by Non-Sensible sentences with the right hand, which differed from both Sensible sentences with the right hand and Non-Sensible sentences with the right hand ($p<.01$). The results are exactly the opposite of the results found in Experiment 1.a and support the simulation hypothesis. In fact, the presence of actions to perform with foot probably led to the inhibition of participants' dominant hand. Given that grasping actions are preferentially performed with the right hand, it is exactly this hand that has to be mostly inhibited. This inhibition might have induced, as a side effect, the advantage in response times of the left over the right hand.

We performed two further 2 (Sensible-Sentence Response Hand: Right vs. Left) X 2 (Sentence Modality: Hand vs. Foot) ANOVAs, one on participants and the other on items, considering only responses to Sensible sentences. We found that right hand responses (*M* = 850 ms) were slower than left hand responses (*M* = 680 ms), both in the analysis with participants as random factor, F^1 (1, 20) = 3.77, *MSe* = 83880.65, *p* =.066, and in in the items analysis, F^2 (1, 11) = 57.44, *MSe* = 3254.09, *p*<.00001. Foot actions were processed 9 ms slower and produced more errors (the percentage of errors was, respectively, 7.95% vs. 4.74% of the sensible trials) than hand actions; however, the effect of Response Hand did not reach significance in the analyses on participants and on items. The interaction between Response Hand and Sentence Modality was not significant, probably due to the order of presentation of the trials (random vs. blocked). Namely, participants may have adopted a general response strategy because foot and hand sentences were presented randomly in the same block.

An independent group of 13 participants evaluated sentences for familiarity on a 7-point scale. In addition, given the peculiarity of foot sentences, we decided to check the imageability of sentences as well. The correlation between the RTs and the familiarity and imageability scores were very low (respectively *r* = -0.18; *r* = -0.04), leading us to exclude the possibility that our results were due to these factors. The reason why we did not pre-select the materials but used post-hoc analyses depends on our study's purpose. Basically we needed noun-verb couples, in which the noun was the same in the two conditions. Using the same name we intended to minimize the effect due to length, age of acquisition, frequency, imageability of different nouns. We dealt with this issue starting the timer at the noun presentation. In Italian it is very difficult to find noun-verb combinations that satisfy our request, that is that can be associated with two verbs referring to actions performed with different effectors.

Discussion

As predicted, the results differed from those obtained in Experiment 1.a as the right hand advantage with sensible sentences was not replicated. This suggests that sentence comprehension implies a simulation of the action described, and that this simulation is quite detailed, as it apparently takes into account the specific effector involved.

However, in the analysis performed only with sensible sentences, the disadvantage of the dominant hand was present both with hand and with foot sentences. This result can be accounted for by the fact that participants may have adopted a general response strategy because foot and hand sentences were presented randomly and not in a blocked way. This account will be tested in Experiment 4.

Sensitivity to the effector involved in the verb-noun combination was demonstrated both by the overall disadvantage of the dominant hand and by the fact that foot sentences lead to the production of more errors than hand sentences. The disadvantage of foot over hand actions replicate the behavioral results found by Pulvermüller et al (2001). In our study this difference between kinds of actions cannot be due to length and frequency of the target-noun, as the noun was the same in both conditions, and can hardly be attributed to familiarity and frequency of the preceding verb, as the timer started when the noun was presented on the screen. Rather, they are probably due to the simulation elicited by the verb-noun combination.

EXPERIMENT 3

Experiment 2 showed that the advantage of the dominant hand was not present when both hand and foot sentences were presented. In Experiment 3 we compared hand and mouth sentences; that is, we used the same noun in combination either with a verb referring to a hand action or to a mouth action (e.g., to peel – the apple vs. to bite – the apple; to grasp – the pill vs. to swallow – the pill).

If we accept that a simulation process takes place during language comprehension, we can advance two possible predictions. First of all, if the simulation driven by the sentence is only effector specific, with sensible sentences there should be a processing difference between hand and mouth sentences, as found by Pulvermüller et al (2001). Alternatively, it is possible that we simulate the action not only at a proximal level, that is at the level of effector, but also at a distal level; that is, that we are sensitive both to the effector referred to by the sentence and to the goal the sentence expresses. If actions are represented and encoded at a distal level, in terms of goals, then the advantage of the dominant hand should be present with both mouth and hand sentences (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Longo, Kosobud, & Bertenthal, 2008). To clarify: a mouth-action, such as licking an ice cream, typically implies / follows a manual action such as, for example, grasping the ice cream. As it can be seen from the examples, all nouns we selected for this experiment afford hand-mouth interaction. The sensitivity both to the effector and the goal would lead to an advantage of the dominant hand with sensible sentences even when the verb refers to actions typically performed with the mouth, such as, for example, "bite an apple".

Method

Participants

Thirty-eight students of the University of Bologna volunteered for the experiment. They were native Italian speakers, with normal or corrected vision, and right-handed according to the Edinburgh Handedness Questionnaire (Oldfield 1971).

Materials

As in Experiment 1, stimuli consisted of pairs composed of a verb and a noun. 56 critical pairs were constructed. 28 object concept-nouns could be preceded either by a verb indicating a prehensile action (e.g. to grasp – the pill; to pick up – the apricot; to cut – the steak; to unwrap – the candy) or an oral action, that is, an action performed with the mouth (e.g., to swallow – the pill; to bite – the apricot; to chew – the steak; to suck – the candy). A further 56 pairs referred to actions which did not make sense.

Procedure

The procedure was exactly the same as in the previous experiments. Participants were divided into two groups. As in the previous experiments, one group was asked to respond “yes” with the right hand and “no” with the left hand; the other group was required to do the opposite.

Results

One participant was eliminated as his/her responses contained errors over 15 %. The error analysis showed no evidence of speed-accuracy tradeoff, so we focused on response time analysis. Data were filtered according to the same criterion used in previous experiments. Removed outliers accounted for 4% of response trials. The remaining response times were entered into a 2 (Sensibility: Sensible vs. Non-Sensible verb-noun combination) X 2 (Mapping: yes-right / no-left vs. yes-left / no-right) mixed factor ANOVA, with mapping as a between participants variable. In the analysis conducted with items as random factor, Sensibility was manipulated between items, whereas Response Hand was manipulated within items.

Participants responded 28 ms more quickly to Sensible than to Non-Sensible sentences, F^1 (1,35) = 7.01, *MSe* = 2011.85, *p*<.05; the effect of Sensibility was significant also in the items analysis, F^2 (1, 54) = 5.06, *MSe* = 4724.36, *p*<.05. More interestingly, even though the factor Mapping did not reach significance in the participants analysis, the predicted interaction between Sensibility and Response Hand was significant in the items analysis, F^2 (1, 54) = 80.63, *MSe* = 1259.62, *p*<.0000001 (see Figure 1 bottom). Newman-Keuls post-hoc analysis indicates that the fastest responses were obtained by Sensible sentences with the right hand, followed by Non-Sensible sentences with the left hand, Sensible sentences with the left hand and, finally, by Non-Sensible sentences with the right hand (*p* <.01). A possible concern regards the discrepancy we found in this experiment between the analysis on participants and the analysis on items A possible cause of this discrepancy might lie in the individual differences among participants. For this reason we selected the 11 faster participants in each condition, thus obtaining a sample of 22 participants, equal in number to the sample of Experiment 2. In the analysis with subjects as random factor, the factor Mapping approached significance, F^1 (1,20) = 3.81, *MSe* = 12738.08, *p* = .065, in keeping with the results obtained in the items analysis. This might suggest that the effect of Mapping is a rather precocious one, and that the effect was obscured when participants employed longer response times. Therefore, the simulation effect can be more clearly detected with fast-respondents than with slow-respondents. Two further 2 (Sensible-Sentence Response Hand: Right vs. Left) X 2 (Sentence Modality: Hand vs. Mouth) ANOVAs were performed, one on participants and the other on items, considering only responses to Sensible sentences. The factor Sentence Modality was significant due to the fact that mouth sentences were 35 ms faster than hand sentences, F^1 (1, 35) = 11,81, *MSe* = 1899.02, *p* < .01; F^2 (1, 13) = 5.64, *MSe* = 4554.56, *p* <. 05. Interestingly, in the items analysis the factor Response Hand was also significant, as right hand responses were faster than left hand responses, F^2 (1, 13) = 25.44, *MSe* = 1861.85, *p* <.0005. As previously explained, this discrepancy with the Participants analysis might be due to the fact that in the participants' analysis the variable Response Hand is not considered per se, as it is embedded in the Mapping factor. The interaction between Response Hand and Sentence Modality was not significant. As in Experiment 2, it is probably due to the fact that mouth and hand sentences were presented randomly in the same block.

As in the previous experiments, 14 participants were required to rate the noun-verb pairs for familiarity on a 7-point scale. Because the correlation between response times and familiarity was quite low (*r* = -0.31), it is possible to exclude the possibility that our results are due to item familiarity.

Discussion

The results replicate those found in Experiment 1.a and are in line with the simulation hypothesis. As predicted, in the analysis performed with all sentences, the fastest responses were obtained through right hand responses to sensible sentences. This suggest that while reading a sentence participants simulate a hand movement necessary either to perform a manual action or to bring to the mouth an object with which to perform the mouth action. More specifically, the advantage of the dominant hand found with both hand sentences and mouth sentences suggests that action information is encoded in terms of goals rather than at a proximal level (Hommel et al., 2001). Consider that with the term goal we do not refer to the final goal. For example, we do not refer to the "relief of headache" that follows the action of swallowing a pill, but to the fact that the hand action typically represents a pre-condition of the mouth action. Thus, for example, the hand is engaged in grasping the pill before swallowing it. This interpretation based on the significance of goals can also account for the results obtained in the analyses performed only with sensible sentences, that is, the fact that faster RTs were obtained with mouth sentences than with hand sentences. Manual actions (at least, the manual actions we selected for this experiment) are typically more general. That is, they can lead to different action sequences and might be justified by different goals. For example, you can grasp an apple in order to put it somewhere else, to bite it, to give it to somebody else, to peel it and so on. On the contrary, mouth actions, even though they activate also hand simulations, are typically more constrained than hand actions, as they tend to refer to a specific goal. For example, biting an apple is simply a way to eat it. An alternative explanation of the advantage of the right hand with both hand and mouth sentences is similar to the one advanced for Experiment 2: it is possible that participants have adopted a general response strategy because mouth and hand sentences were presented randomly and not in a blocked way.

EXPERIMENT 4

In Experiment 2 we found slower RTs with the right than with the left hand and in Experiment 3 a facilitation of the right hand. However, the analyses on sensible sentences did not show any dominant hand advantage in the hand over the foot sentences (Experiment 2) and in the hand over the mouth sentences (Experiment 3). The results obtained in Experiment 2 and 3 could be due to the fact that participants may have adopted a general response strategy because foot and hand sentences (Experiment 2) and mouth and hand sentences (Experiment 3) were presented randomly in the same block. Other studies in different areas have demonstrated the effects of the composition of the experimental list (random vs. blocked presentation) on behavioural tasks (e.g., Tessari & Rumiati, 2004). Experiment 4 was designed to address whether the random vs. blocked presentation of the stimuli may have influenced the results. Namely, we presented the sentences in a blocked way and asked right-handed participants to respond to sensible sentences with the right hand and to non sensible sentences with the left one. If the absence of the right-hand facilitation effect in Experiment 2 and 3 was due to the random presentation of the stimuli, we predict to find a facilitation of right-hand responses with hand compared to foot sentences, but no facilitation with hand compared to mouth sentences.

Method

Participants

Eight volunteers took part in the experiment. They were selected according to the same criteria used in previous experiments.

Materials

The materials were the same of the previous experiments. The only difference consisted in the blocked presentation of the stimuli. Stimuli were presented in 4 different blocks, two including the foot sentences and the hand sentences presented in Experiment 2, and two including the mouth sentences and the hand sentences presented in Experiment 3. The block presentation order was balanced across participant.

Procedure

All participants were asked to respond “yes” with their right hand and “no” with the left hand.

Results

All incorrect responses were eliminated. Errors analyses did not show any evidence of a speed-accuracy tradeoff. To screen for outliers, we used the same criterion as in the previous experiments. Removed outliers accounted for 4.52 % (Foot-Hand Block) and 4.90 % (Mouth-Hand Blocks) of response trials. The remaining response times were submitted to four different ANOVAs, two for each pair of blocks (‘hand sentences’ vs. ‘mouth sentences’; ‘hand sentences’ vs. ‘foot sentences’), one with participants and another with materials as random factor. The reason why we did not analyze the data with a 3 levels ANOVA (foot-hand-mouth) was that the nouns were not the same for the three conditions.

Foot and Hand Blocks

RTs were submitted to two 2 (Sensibility: yes, sensible vs. no, no-sensible) X 2 (Sentence Modality: Hand / Foot sentence) ANOVAs, with Sentence Modality and Sentence Sensibility as within participants and within items variables.

Right hand responses were 192 ms faster than left hand responses, F^1 (1, 7) = 21.94, *MSe* = 3364, 31, $p<.005$; the effect was significant also in the items analysis, F^2 (1, 11) = 7.64, *MSe* = 13.828.99, $p< .05$. Crucially, in the participants analysis the interaction between Sensibility and Sentence Modality was significant, F^1 (1, 7) = 6.42, *MSe* = 1974.90, $p<.05$; F^2 (1, 11) = 1.87, *MSe* = 9260.82, $p<.19$ (see Fig. 2 top). Newman-Keuls post-hoc analysis indicates that the fastest responses were obtained in responses triggered by Hand Sentences with the right hand. With hand sentences, right hand responses were 136 ms faster than left hand responses (p =.002), whereas with foot sentences they were only 56 ms faster than left right responses (p =.04).

Insert Figure 2 about here

Mouth and Hand Blocks

We performed the same ANOVAs with the same factors as in the previous analysis: 2 (Sensibility: yes, sensible vs. no, no-sensible) X 2 (Sentence Modality: Hand / Mouth sentence) ANOVAs. Participants responded 39 ms more quickly with the Right than with the Left hand, F^1 (1,7) = 4.31, *MSe* = 2802.61, $p<.07$; the same effect was found in the items analysis, F^2 (1,11) = 8.49, *MSe* = 1715.829, $p< .05$. More interestingly, as in Experiment 3, mouth sentences were responded to 70 ms more quickly than hand sentences, F^1 (1, 7) = 11.90, *MSe* = 3306.93, $p<.01$; F^2 (1, 11) = 8.66, *MSe* = 6195.619, $p< .01$. As predicted, no interaction was found (see Fig. 2 bottom).

Discussion

The results of this control experiment suggest that the missing effect of Experiment 2 was due to the random presentation of the stimuli. This was not the case for Experiment 4. Thus we can conclude that the comprehension of hand and mouth sentences leads to the activation of the right hand, whereas this is not true for foot sentences. This confirms that sentence comprehension implies a simulation of the action described, and that this simulation takes into account the specific effector involved.

GENERAL DISCUSSION

The results found across the 4 experiments are in line with the predictions of the embodied theory. Namely, they suggest that the comprehension of the meaning of verb-noun pairs implies a mental simulation. This simulation is quite detailed, as it is modulated both by the kind of effector the sentence refers to (hand, foot, mouth), and by the specific hand (dominant, non-dominant) the action expressed by the sentence typically involves. As to the differences due to the kind of effector involved, noun-verb pairs referring to mouth actions were processed faster than pairs referring to hand actions, and the latter were processed faster than pairs referring to foot actions. These results are consistent with the behavioral results found by Pulvermüller et al. (2001), who found a difference in lexical decision between face-, arm- and leg- related verbs. However, our study differs from Pulvermüller et al's for two main reasons. First of all, the effect we found concerned noun-verb pairs (sentences) rather than single verbs. Secondly, we used a method implying a deeper processing of the words' meaning instead of a lexical decision task. We also found a difference between the dominant and the non-dominant hand. As predicted, the advantage of the dominant hand concerned sensible sentences related both to hand and to mouth (Experiment 1.a and 3). Significantly, the facilitation of the dominant hand with hand and with mouth sentences was present only with sensible sentences, thus confirming the hypothesis that it was due to a simulation process and not to a general advantage of the right over the left hand. In Experiment 2, in which sensible sentences referred to actions involving both hand and foot, we found slower RTs with the right than with the left hand rather than a facilitation of the right hand. The missing effect of hand sentences with the dominant hand in Experiment 2 was due to the random presentation of hand and foot sentences. Namely, in Experiment 4, when hand and foot sentences were presented in different blocks, we found a marked advantage of the dominant hand with sensible hand sentences, but not with sensible foot sentences. The analyses of sensible sentences allowed us to draw some conclusions regarding the role played by the effectors and the importance of goals in simulating. We believe the advantage of the dominant hand obtained with both hand and mouth sentences (even if mouth sentences were processed faster than hand ones) to be particularly significant because it means, by implication, that during sentence comprehension participants are sensitive both to the effector involved and to the goals expressed by the sentence. Namely, mouth-related actions as "biting an apple" imply the simulation of the whole process of eating the apple, including bringing it to the mouth with the hand. On the contrary, the hand is typically not involved in foot related actions, such as "kicking a ball".

Our study is in line with studies showing the deep interrelationships between language and motor system. We will briefly review recent evidence suggesting that words activate the motor system. First, there is evidence that the semantic meaning of words affects the grasping and reaching kinematics (Gentilucci, 2003). For example, Glover and Dixon (2002) found that the meaning of the words "large" or "small" printed on objects had an effect on the grip aperture in the initial grasp kinematics. Second, behavioral evidence shows that words activate motor information (Tucker & Ellis, 2004). For example, Borghi, Glenberg, & Kaschak (2004) found with a part verification task that participants responded more quickly when required to press a button in a direction compatible with an object's part location (e.g. responding upward to verify that a horse has a head) than when responding in a direction incompatible with the part location. Other studies focused on the mental simulation activated while processing sentences rather than single words. With a sentence sensibility task Glenberg and Kaschak (2002) found that response times were faster in case of congruency between the movement implied by the sentence (away vs. toward, e.g., "to close the drawer" vs. "to open the drawer") and the direction implied by the movement required to respond. Recent studies on sentence comprehension suggest that the simulation triggered by the sentence is quite detailed (see for example Bergen & Wheeler, 2005; Richardson, Spivey, McRae & Barsalou, 2003; Scorolli & Borghi, 2007; Spivey & Geng, 2001). Zwaan, Madden, Yaxley and Aveyard (2004) asked participants to listen to sentences implying a movement toward or away, such as, for example: "The kids tossed the beach-ball over the sand toward you" vs. "You tossed the beach ball over the sand towards the kids.” After listening to the sentence, participants were shown two sequentially presented objects, one larger and another smaller, implying either a movement toward the observer (if the smaller object was followed by the larger one) or away (if the larger object was followed by the smaller one) from him / her. They found a congruency effect between the movement implied by the sentence and the visual object presentation sequence. Kaschak, Madden, Therriault, Yaxley, Aveyard, Blanchard and Zwaan (2005) asked participants to evaluate whether or not sentences implying different kinds of motion (away, towards, up- and downwards: e.g., “The car left you in the dust”, motion away) made sense. At the same time, they presented visual stimuli moving either in the same or in the opposite direction as that implied by the sentence. The interference effect they found suggests that the simulation is quite detailed, and that the same neural areas are recruited while processing motion sentences and observing motion stimuli (for a more detailed discussion on the differences between interference and facilitation effects in studies on language and motor system, see Borreggine & Kaschak, 2006; De Vega, Robertson, Glenberg, Kaschak & Rinck, 2004). Recent support for a simulationist view of language comprehension is also provided by Zwaan and Taylor (2006). They showed that sensibility judgments for manual rotation sentences were made more quickly when the manual response to the sentence was in the same rotation direction as the manual action described by the sentence. This suggests that comprehension of manual rotation sentences produces motor resonance, as evidenced by the effect of this of sentence comprehension on actual motor responses. In addition, they showed that motor resonance during sentence processing occurred relatively quickly and locally. By asking participants to read sentences like “Before /the / big race / the driver / took out / his key / and / started / the / car” while turning the knob one frame at a time, they found that the advantage in cases of congruency between actual turning direction and the motion implied by the sentence was localized in the verb region. In line with the reported findings, our study shows that sentence comprehension activates a simulation process. Importantly, this simulation is quite detailed, as it is modulated both by the kind of effector the sentence refers to (hand, foot, mouth), and by the specific hand (dominant, non-dominant) the action expressed by the sentence typically involves. Accordingly, our study shows that objects affordances influence not only the understanding of nouns referring to objects but also the understanding of different kinds of words and of more complex linguistic structures, such as different kinds of words combinations. As MacWhinney (1999) puts it, not only nouns but verbs as well provide affordances and elicit simulations: “when we hear the word walk, we immediately activate the basic elements of the physical components of walking. These include alternating motion of the legs, counterbalanced swinging of the arms, pressure of the knees and other joints, and the sense of our weight coming down on the earth” (p. 219).

A last point is worth noticing. We believe our study has implications for studies on the neural basis of language understanding. The relevance of goal we found is consistent with the idea of motor resonance, with ideomotor theories (e.g., Prinz, 1997) and with the recent evidence found by Umiltà, Kohler, Gallese, Fogassi, Fadiga, Keysers and Rizzolatti (2001), that mirror neurons fire in accordance with the activated goal, and not only with the activated effector. From a neural point of view, the similar effects found with the mouth and the hand sentences are justified by the common activation of the Broca area (Buccino et al., 2001). This is convergent with evidence indicating that at the neural level hand and mouth actions activate contiguous regions, which is not the case with foot and hand actions. Our study confirms the existence of a strict interrelationship between hand

and mouth actions and it is in line with recent studies showing that language evolves from gestures and manual actions (e.g., Corballis, 2002; Arbib , 2005; Parisi, Borghi, Di Ferdinando & Tsiotas, 2005).

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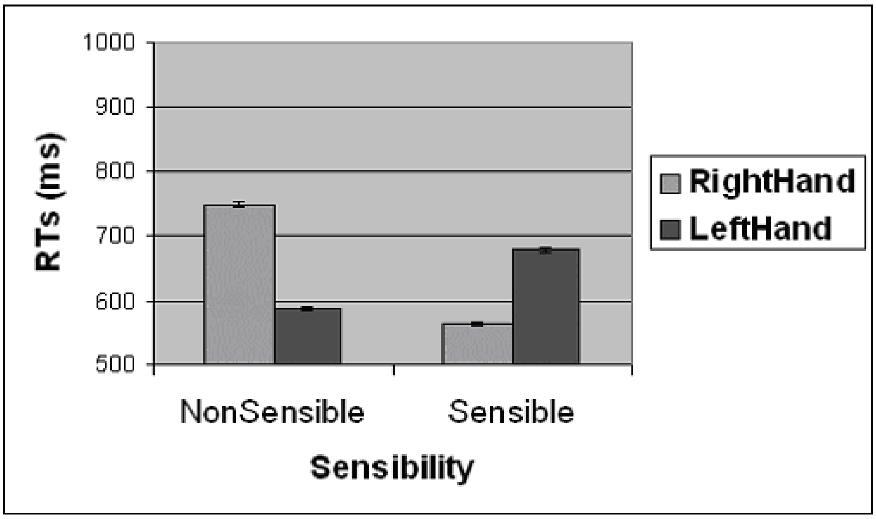
Figure captions

Figure 1. The interactions between Response Hand and Sensibility in Experiment 1a, 2, and 3. Means on items. Bars represent standard error.

Figure 2. The interaction between Response Hand and Sentence Modality in Experiment 4. Bars represent standard error.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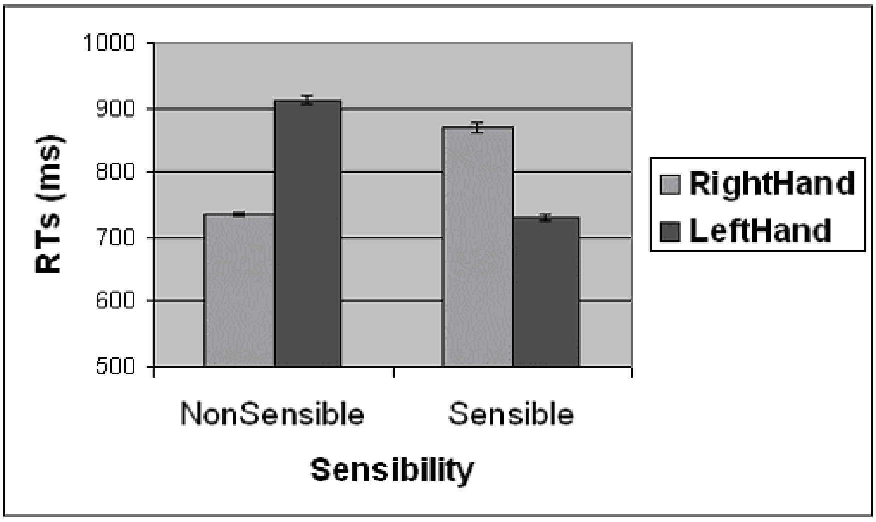
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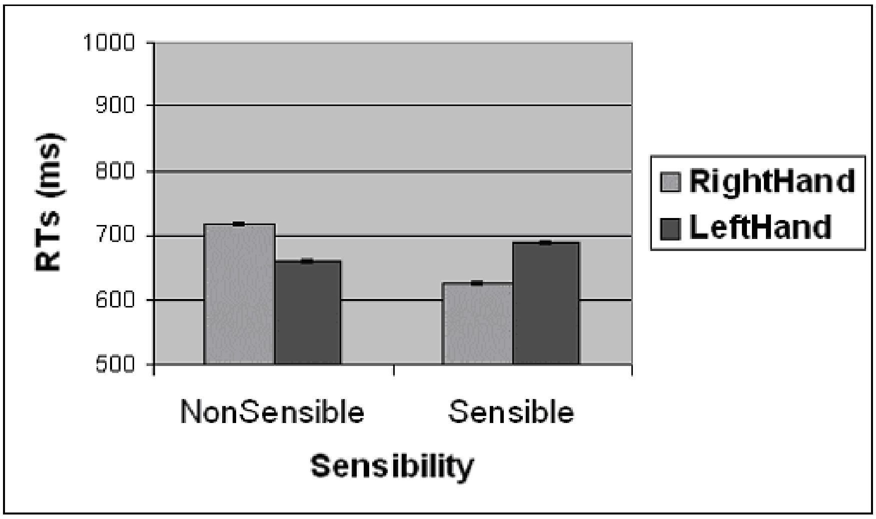
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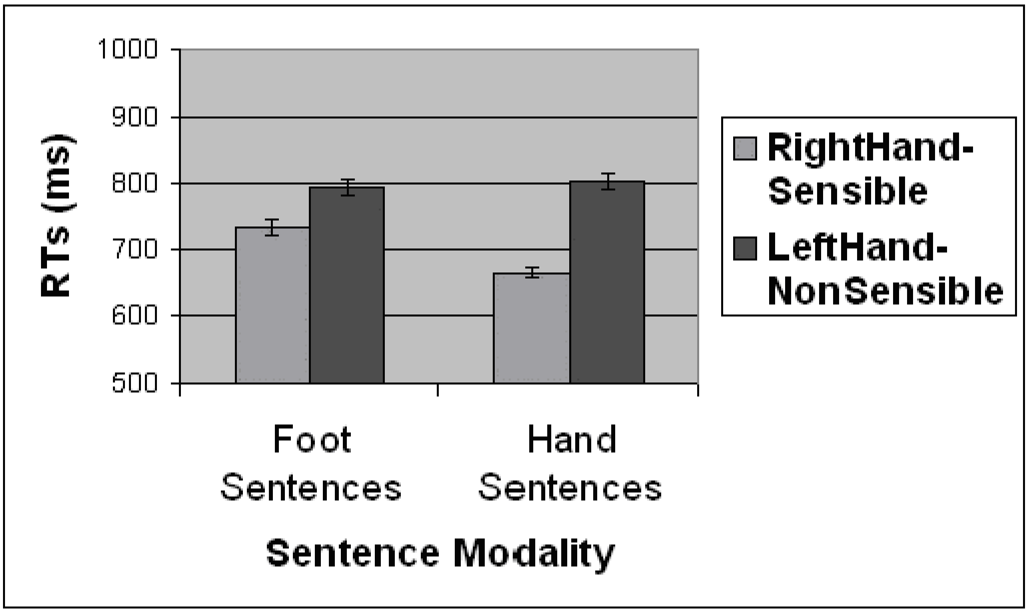
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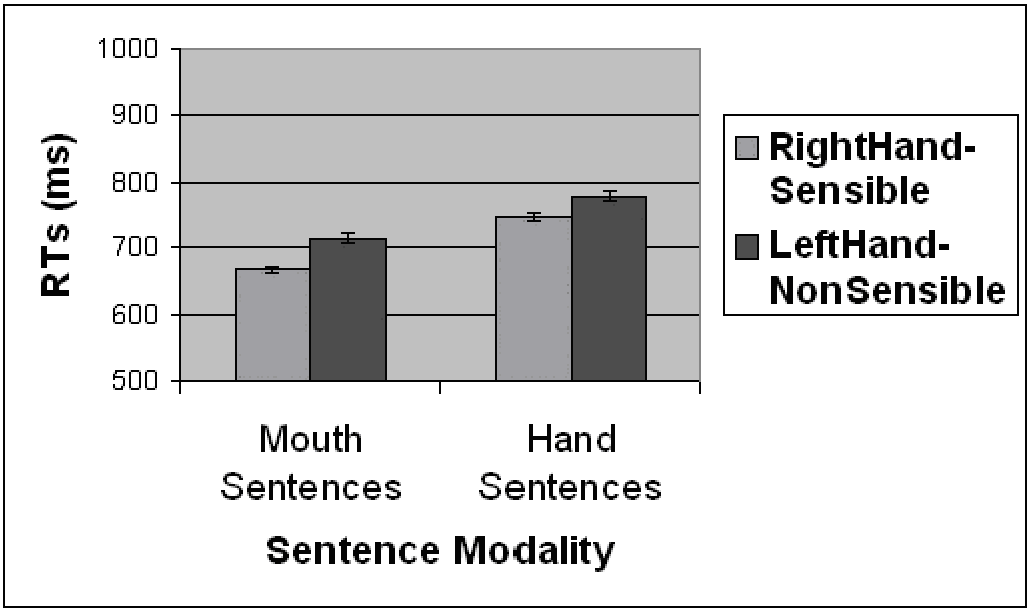
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