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Task related modulation of the motor system during language processing

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ABSTRACT

Recent neurophysiological and brain imaging studies have shown that the motor system is involved in language processing. However it is an open question whether this involvement is a necessary requisite to understand language or rather a side effect of distinct cognitive processes underlying it. In order to clarify this issue we carried out three behavioral experiments, using a go-no go paradigm. Italian verbs expressing hand actions, foot actions or an abstract content served as stimuli. Participants used their right hands to respond. In Experiment 1, in which a semantics decision task with an early delivery of the go signal (during processing language material) was used, slower responses were found for hand action-related verbs than for foot action-related verbs. In Experiment 2, using the same task with either an early or a delayed delivery of the go signal (when language material had been already processed), no difference was found between responses to the two verb categories in the delayed delivery condition. In Experiment 3, in which a lexical decision task with an early delivery of the go signal was used, again no difference between the two verb categories was found. The present findings demonstrate that during language processing the modulation of the motor system crucially occurs while performing a semantics decision task, thus supporting the notion that this involvement is a necessary step to understand language rather than a side effect of upstream cognitive processes.

Keywords: Language; Mirror neuron system; Embodied theories of language; Lexical decision

task; Semantics decision task.

INTRODUCTION

The precise neural mechanisms underlying language understanding remain largely debated. According to a classical view, language understanding relies on symbolic, amodal mental representations (e.g., Fodor, 1975). Following this approach, the meaning of language derives from an arbitrary correspondence between abstract symbols and their corresponding extensions in the world. An alternative hypothesis assumes that language understanding relies on 'embodiement' (Lakoff, 1987; Glenberg, 1997; Barsalou, 1999; Pulvermüller 2002; Zwaan, 2004; Gallese and Lakoff, 2005; *Zwaan and Taylor, 2006;* Glenberg, in press). Based on this view, language understanding implies the involvement of the neural systems used when perceiving or acting.

Focusing on action-related language material, recent neurophysiological data have provided with experimental evidence that the motor system is involved during language processing. In a high resolution electroencephalographic (EEG) study, using leg and face actions-related verbs and pseudo-words in a lexical decision task (i.e. deciding whether a letter string is a word or not), Pulvermüller, Harle and Hummel (2001) showed that, event-related potentials were differently located for the action-related verbs. While leg-related verbs entailed an activity focus close to the vertex, overlapping with the motor representations of leg movements, the face-related verbs produced a focus above the cortical representation of the face and mouth movements. Recent functional brain imaging studies confirmed this

'somatotopic' activation of the motor system during processing of effector-related language material. In an fMRI study Hauk, Johnsrude and Pulvermüller (2004) found a nearly similar somatotopic organization while using a passive reading task involving face, leg and arm action-related verbs. With the same technique Tettamanti and colleagues (2005) showed that listening to sentences expressing actions performed with the mouth, the hand or the foot, respectively, led to signal increase in different sectors of the premotor cortex, strictly depending on the effector involved in the listened-to action related sentence. Furthermore, Aziz-Zadeh and colleagues (2006) found in the left premotor cortex common activations both during the observation of actions and the processing of sentences expressing those same actions.

Also consistent with the involvement of the motor system during language processing are the results of a recent transcranial magnetic stimulation (TMS) study, showing that motor-evoked potentials (MEPs) recorded from hand muscles are specifically modulated during listening to sentences expressing hand-related actions, while MEPs recorded from foot/leg muscles are similarly modulated during listening to sentences expressing foot-related actions (Buccino et al., 2005).

Altogether, these data demonstrate that processing verbally presented actions modulates the activity of the motor system and suggests the existence of shared neural substrates for understanding observed actions and action-related language material. These findings may be explained by the functional properties of the 'mirror neuron' system, consisting

of a particular set of premotor and parietal brain regions, which has been shown to play a role in action understanding (Buccino, Binkofski and Riggio, 2004; Rizzolatti and Craighero, 2004; Buccino, Solodkin, Small, 2006). This system is activated not only during the execution of actions but also during action observation and listening to common action-related sounds, both in non-human primates and humans (e.g., Di Pellegrino et al., 1992; Rizzolatti et al., 1996; Gallese et al., 1996; Buccino et al., 2001; Kohler et al., 2002; Ferrari et al., 2003; Keysers et al., 2003; Aziz-zadeh et al., 2004). Furthermore, it appears to be somatotopically organized, as demonstrated by brain imaging studies (Buccino et al., 2001; Wheaton et al., 2004; Sakreida et al., 2005). From these findings, it has been argued that such a system might play a role in building up action concepts (Rizzolatti and Arbib, 1998; Gallese and Lakoff 2005; Rizzolatti and Buccino, 2005) and, by extension, might participate to language processing at least as far as action-related language material is concerned (Gallese and Lakoff, 2005; Rizzolatti and Buccino, 2005).

While suggesting a recruitment of the motor system during language processing, the studies reviewed so far do not disentangle whether the involvement of the motor system is a necessary step to understand the presented language material or rather a *side-effect* of distinct upstream processes involved in understanding language (see also Mahon and Caramazza, 2004). To address this issue, we carried-out three behavioral experiments, using a go-no go paradigm. Italian verbs expressing hand actions, foot actions or abstract contents served as

stimuli. Throughout experiments we varied the linguistic task and the delivery time of the go signal. This allowed us to define the possible functional role of the motor system in different language processing tasks.

METHOD

Subjects

Sixty participants entered the study: twenty-four (mean age ± SD, 24 ± 5 years) in Experiment 1, twenty-four (mean age ± SD, 23 ± 3 years) in Experiment 2 and twelve (mean age ± SD, 22 ± 2 years) in Experiment 3. All participants were native Italian speakers. All were right-handed, according to a standard handedness inventory (Oldfield, 1971), had normal or corrected-to-normal vision and reported no history of speaking or hearing disorders. None of them was aware of the purpose of the experiment.

Stimuli

In Experiments 1 and 2, the stimuli were presented both in the visual and in the acoustic modality. Thirty Italian verbs were selected (see Appendix): ten verbs expressed a hand-related action (e.g., 'applaudire', 'to applaud'), ten a foot-related action (e.g., 'marciare', 'to walk'), and ten an abstract content (e.g., 'amare', 'to love'). All verbs were presented in the infinitive form and could be three or four syllables long. Verbs in the three categories were matched for syllable number (average values: 3.5, 3.7 and 3.5 syllables for hand-related, foot-related and abstract verbs, respectively) and for word-length (average values: 8.5, 8.8 and 7.7 letters for hand-related, foot-related and abstract verbs, respectively). Mean lexical frequency for hand, foot and abstract-related verbs was 3.03, 8.42 and 9.64 (in occurrences per million), respectively (Laudanna et al., 1995 - ~ 3.798.000 words). A one-way analysis of variance with three levels, one for each verb category, showed no reliable differences ($F(2, 27) = 1.06$, $p = .35$).

For auditory presentation, each verb was recorded by a native female speaker of Italian and digitized in an individual sound file at a sampling rate of 48-kHz with 16-bit quantization

recording. For each sound file, the isolation point (Marslen-Wilson, 1990) was detected on the stimulus spectrogram using Praat software (Institute of Phonetic Sciences - University of Amsterdam). This procedure allowed to determine the precise time at which the verb could be correctly identified. The three verb categories were matched for duration (average values: 1.40, 1.41 and 1.39 s. for hand-related, foot-related and abstract verbs, respectively) and for the interval between the beginning of the acoustic presentation and the isolation point of the verb (average values: were 0.68, 0.68 and 0.64 syllables for hand-related, foot-related and abstract verbs, respectively).

In Experiment 3, twenty verbs and twenty nonsense words were selected. Ten verbs expressed a hand-related action, ten a foot-related action. They were identical to those used in Experiment 1 and 2. Nonsense words were built by replacing one consonant into the first or the second syllable of each verb (e.g., 'firtare' instead of 'firmare'). With this procedure, verbs and nonsense words were matched for syllable number (average values: 3.5, 3.7 and 3.6 syllables for hand-related verbs, foot-related verbs and nonsense words, respectively) and for word-length (average values: 8.5, 8.8 and 8.7 letters for hand-related verbs, foot-related verbs and nonsense words, respectively). *In no case nonsense words contained orthographically or phonologically illegal bigrams for the Italian language.*

Procedure

In Experiment 1, twelve participants were presented with auditory stimuli and twelve with visual stimuli. The experiment was carried out in a sound-attenuated room, dimly illuminated by a halogen lamp directed towards the ceiling. Participants sat comfortably in front of a computer screen at a distance of about 60 cm from it, with the right hand placed over a round-shaped knob (6 mm diameter), positioned on the right side of the computer screen.

Participants were instructed to carefully listen-to/read verbs and to give a motor response, as fast and accurately as possible by pressing with the right index finger the knob, when the verb expressed a concrete action, and refrain from responding when the verb expressed an abstract content (go – no go paradigm).

Acoustic stimuli were delivered by a PC at a comfortable sound level by means of two loudspeakers, located on both sides of the PC at the same distance from participants. Visual stimuli were presented at the center of the computer screen and written in white lowercase Arial font on a black background.

During the experiment, each verb belonging to the three categories was presented twice. Thus the experiment consisted of 60 trials, run in a single session. Stimuli were randomized for each subject. Whatever the modality of stimulus presentation, each trial started with a red circle presented at the center of the screen. After a variable delay of 150-500 ms (in order to avoid a response habituation), a verb was acoustically or visually presented. In the auditory presentation, the red circle changed to green in coincidence with the isolation point of the verb. In the visual presentation, the red circle changed to green, after a fixed time of 150 ms from the onset of verb presentation. *This time has been shown to be sufficient to get recruitment of frontal areas during reading (Hauk and Pulvermüller, 2004).* The colour change of the circle was the 'go' signal for the response when the verb expressed a hand or foot action related verb. Intertrial interval was 3 sec. During this period the PC screen remained blank.

In Experiment 2, the go-signal for the response was delivered at two distinct time points from the verb presentation. In the auditory modality, the go-signal appeared, in half of the trials, either at the isolation point (early delivery) or 1000 ms after the isolation point (delayed delivery). In the visual modality, the go-signal appeared, in half of the trials, either 150 ms

(early delivery) or 1150 ms after the onset of the verb presentation (delayed delivery). During the experiment, each verb of the three categories was presented twice for each time point at which the go signal was given (normal and 1 sec delayed). As whole there were 160 trials run in a single session. Verbs sequences were randomized for each participant.

In Experiment 3, a lexical decision task was used in which participants were instructed to give a response when the stimulus was a word and refrain from responding when the stimulus was a nonsense word. As in the previous experiments participants gave their responses using their right-index. The stimuli were presented only in the visual modality with the go signal delivered 150 ms after the onset of the verb presentation. During the experiment, each stimulus was presented twice. Thus, overall 80 trials were given in a single session. Verbs sequences were randomized for each subject.

Data analysis

Trials in which reaction-times (RTs) from the go-signal were faster than 130 ms (anticipations) or slower than 1000 ms (missing responses) were considered as errors and discarded without replacement. In Experiment 1, three participants in the visual presentation modality and one participant in the auditory presentation modality were removed from the analysis because their error rates exceeded 10% (anticipations, missing responses or wrong semantics coding). The mean percentage of errors was 7.0% and 4.7% in the visual and auditory presentation modalities, respectively. In Experiment 2, no participants exceeded the error limit of 10%. The mean percentage of errors was 4.0% and 2.5% in the visual and auditory presentation modalities, respectively. In Experiment 3, three participants were removed from the analysis because their error rates exceeded 10% (anticipations, missing responses or wrong lexical coding). The mean percentage of errors was 4.9%.

For each participant, median values for correct RTs were calculated for each verb category. These data entered an analysis of variance (ANOVA) for each experiment. In Experiment 1, two variables were considered: verb category (hand or foot action) as a within-subjects variable and stimulus modality (auditory or visual) as a between-subjects variable. In Experiment 2, verb category (hand or foot action) and time point (early or delayed) were treated as within-subjects variables and stimulus modality (auditory or visual) as a between-subjects variable. Finally, in Experiment 3 an ANOVA was carried out with verb category (hand or foot action) as a within-subjects variable.

RESULTS

Experiment 1

Data are shown in Figure 1A. ANOVA showed that the main effects of verb category ($F(1,18) = 25.64$, $p < .001$) and modality of presentation ($F(1,18) = 19.63$, $p < .001$) were significant. The interaction between these two variables ($F(1,18) = 0.59$) was not significant.

Insert Figure 1 about here

The effect of modality is due to faster responses in the auditory presentation (279 ms) than in the visual presentation (401 ms). This effect may not only depend on the modality of stimulus presentation per se, but also on the fact that the go-signal delivery was on average later for auditory stimuli than for visual stimuli (670 ms vs. 150 ms respectively). The effect of verb category is the most interesting result. Responses to hand action-related verbs (352 ms) were slower than responses to foot action-related verbs (317 ms). Furthermore, this effect was of the same magnitude whatever the modality of presentation. This result indicates that responses were slower when participants responded with the same effector involved in the actual execution of the action expressed by the verb.

Experiment 2

Data are shown in Figure 2. ANOVA showed the main effects of verb category ($F(1,22) = 13.41$, $p < .005$), modality of presentation ($F(1,22) = 21.25$, $p < .005$) and time of go signal delivery ($F(1,22) = 189.06$, $p < .001$) were significant. The interactions between time of go

signal delivery and modality of presentation ($F(1,22) = 49.34$, $p < .001$) and between time of go signal delivery and verb category ($F(1,22) = 10.77$, $p < .005$) were also significant.

Insert Figure 2 about here

As in Experiment 1, the effect of modality may be due to faster responses in the auditory presentation (241 ms) than in the visual presentation (318 ms). The effect of verb category is due to slower responses to hand action-related verbs (286 ms) than to foot action-related verbs (272 ms). Most interesting, however, is the effect related to the time of go signal delivery, showing that RTs were slower at the early than at the delayed delivery of the go signal (350 ms vs. 209 ms respectively). Furthermore, the two interactions indicate that, when the go signal was delayed, both the differences between verb categories and presentation modalities disappeared. Indeed, in the delayed delivery, RTs were of the same magnitude whatever the modality or the category of the verb (211 ms vs. 208 ms, respectively), thus suggesting that the modulation of the motor system is transient, time-locked to the semantic processing of language material.

Experiment 3

Data are shown in Figure 1B. Interestingly, using a lexical decision task, the main effect verb category did not reach the statistical significance ($F<1$), although responses to hand action-related verbs (405 ms) were slightly faster than those to foot action-related verbs (415 ms).

A further ANOVA was carried out on the data from Experiment 3 and those from Experiment 1 related to the visual modality, in order to assess the role of the linguistic task (semantic vs. lexical decision), with verb category (hand or foot action) as a within-subjects variable and task as a between-subjects variable. Only the interaction between the two variables was significant ($F(1,16) = 9.29$, $p < .01$). In spite of the fact that the performance in the two linguistic tasks did not differ (401 ms vs. 410 ms respectively, $F(1,16) = 3.48$), post-hoc comparisons (Newman-Keuls) showed that only in Experiment 1, in which a semantic decision task was required, responses were slower when the effector involved in the actual execution of the processed verb was the same used to give the motor response ($p < .02$, see Figure 1B). On the contrary, when a lexical decision task was required no significant effect was detected for verb category ($p > 0.41$).

GENERAL DISCUSSION

In Experiment 1, in which participants were asked to give a manual response when the verb expressed a concrete action, slower responses were found for hand action-related verbs than for foot action-related verbs, regardless of the modality of presentation. In a combined TMS and behavioral study, Buccino et al. (2005) found, during listening to foot and hand action-related sentences as compared to abstract content related sentences, a decrease of MEPs amplitude and slower RTs, when these parameters were collected from the same effector (foot or hand, respectively) implied in the listened to action-related sentences. The authors interpreted these findings assuming that motor representations involved in processing the listened to language material were the same recruited to give the response, explicitly in the behavioral study or implicitly in the TMS study, thus leading to an interference effect. In Experiment 1 of the present study these findings were fully confirmed and extended to visually presented verbs. Regardless of the presentation modality, processing action related language material similarly involves the motor system. The resulting interference effect is most likely due to the simultaneous involvement of the motor system in both understanding the listened to or read language material and executing the required response and the consequent competition for common resources between motor response and language processing.

Altogether these results are consistent with the embodiment theory for language

understanding that suggests that neural systems for perception and action are also engaged during language comprehension (Lakoff, 1987; Glenberg, 1997; Barsalou, 1999; Pulvermüller 2002; Zwaan, 2004; Gallese and Lakoff, 2005; *Zwaan and Taylor, 2006;* Glenberg, in press). However, these results do not allow to distinguish whether this recruitment of the motor system is necessary for the comprehension of language or just an accompanying phenomenon of it: participants could image the action expressed by the sentence or they could plan the execution of those actions or, in more general terms, activate a motor representation as in those conditions defined as S states by Jeannerod (2001). One may argue that if the recruitment of the motor system is a fundamental step to understand language material, this modulation should intervene at the very moment in which participants "catch" the meaning and therefore be strictly time-locked with it. Further, this recruitment should be linked to a full comprehension of the meaning of the language material and therefore not present when the task does not require it in order to be solved. Experiments 2 and 3 provide with evidence in this direction. In Experiment 2 the interference effect was present in the early delivery of go signal but not in the delayed delivery of it. This finding is important for two reasons: first, it shows that the interference effect is time-locked to the process of verb understanding; second, the absence of this modulation in the delayed delivery of go signal testifies that the involvement of the motor system is not an accompanying phenomenon of the language task, but has a fundamental role in solving the task.

In Experiment 3, where a lexical decision task was used, no significant difference between the two verb categories was found, showing that the interference effect was restricted to the semantic task. These results are in keeping with the study of Pulvermüller, Harle and Hummel (2001) that, in their Experiment 2, with a design overlapping the present one, found hand responses to hand-related verbs slightly faster than responses to foot-related verbs. Similar results (namely a facilitation in responses given with a specific effector, when the effector involved in the language material is the same) were also obtained in a very recent study, when nouns rather than verbs were used (Scorolli and Borghi, 2006). Since in Experiment 3 we only used an early delivery of the go signal, *the present findings show that the motor system is differently modulated according to the language task. Results similar to those obtained in the present study during the semantic decision tasks (Experiments 1 and 2) were obtained by Boulenger et al. (2005) in a lexical decision task, using kinematics parameters. In contrast to our conclusion, these authors stressed a different modulation of the motor system over time during language processing, with an early interference effect followed by a facilitation effect. In this study sensitive stimuli were verbs referring to actions done with the mouth, hand and foot and nouns referring to concrete entities that cannot be manipulated. The results showed that verbs but not nouns affected the motor responses. The concomitant presence of words with a specific motor content (verbs) and words with no motor content (nouns) introduces a major confound in the study making the results questionable. The possibility*

raises, in fact, that their results could express a different way to process verbs and nouns, as grammar categories, in the brain, rather than a time course of modulation in the motor system during the language task. In the present study the only difference between Experiment 1 and 3 was the language task required by participants, with the consequence that only the task itself can explain the different results. Indeed, in the first two experiments a semantic analysis of the stimulus was crucial in order to distinguish between action-related and abstract-content verbs. In contrast, in Experiment 3, since nonsense words differed from sensible words (verbs) only for the replacement of one consonant, participants solved the task most likely relying on processing the phonological aspects of the verbs (see Fadiga et al., 2002) rather than retrieving their semantic contents. Although it cannot be ruled out that the semantic level could be reached in a lexical decision task, this processing was not necessary to correctly perform it and therefore not used to solve it. This suggests that the interference effect, possibly related to an actual simulation of the content of the verb, occurs when an explicit semantic representation is implied by the task. The evidence that we did not find any interference effect with the lexical decision task testifies that not only the motor system was less deeply involved in this condition, but also that the nature of this involvement is different. In the case of the semantic decision an actual simulation is active as demonstrated by the competition of resources in the same neural substrate, whereas in the lexical decision task a modulation of the motor system (if any) may be interpreted as the result of possible associations between action words and their

corresponding motor representations, that most likely occur during development.

Further investigations are of course necessary to confirm this view. In particular, as clearly stated by Mahon and Caramazza (2005), a solid confirmation to the embodied language approach could come from clinical studies evidencing that "effectively removing motor structures impairs the ability to understand verbs describing body actions". So far, unfortunately, to the best of our knowledge, no studies have systematically investigated language processing in patients with lesions centered in the motor system. As a matter of fact, this should be a matter of further investigations. On the other hand, some neuropsychological studies (Bak et al 2001; Damasio and Tranel,1993,; Bell, 1994) have shown selective deficits for processing action words after left premotor lesions, thus supporting the notion, also at clinical level, that language processing and action share to some extent the same neural structures.

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FIGURE LEGEND

Figure 1. Mean reaction times found in Experiment 1 in which a semantic decision task was used (A) and Experiment 3 in which a lexical decision task was used (B). In Experiment 1 stimuli were auditory or visually presented, while in Experiment 3 they were only visually presented. Bars represent standard errors.

Figure 2. Mean reaction times to auditory and visually presented stimuli in Experiment 2 in which a semantic decision task was used. Go signal was delivered at the isolation point (early delivery) in the acoustic presentation and after 150 ms (early delivery) in the visual presentation and after 1sec (delayed delivery). Bars represent standard errors.