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Nouns referring to tools and natural objects differentially modulate the motor system

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ABSTRACT

While increasing evidence points to a critical role for the motor system in language processing, the focus of previous work has been on the linguistic category of verbs. Here we tested whether nouns are effective in modulating the motor system and further whether different kinds of nouns – those referring to artifacts or natural items, and items that are graspable or ungraspable – would differentially modulate the system. A Transcranial Magnetic Stimulation (TMS) study was carried out to compare modulation of the motor system when subjects read nouns referring to objects which are Artificial or Natural and which are Graspable or Ungraspable. TMS was applied to the primary motor cortex representation of the first dorsal interosseous (FDI) muscle of the right hand at 150 ms after noun presentation. Analyses of Motor Evoked Potentials (MEPs) revealed that across the duration of the task, nouns referring to graspable artifacts (tools) were associated with significantly greater MEP areas. Analyses of the initial presentation of items revealed a main effect of graspability. The findings are in line with an embodied view of nouns, with MEP measures modulated according to whether nouns referred to natural objects or artifacts (tools), confirming tools as a special class of items in motor terms. Additionally our data support a difference for graspable versus non graspable objects, an effect which for natural objects is restricted to initial presentation of items.

1. Introduction

The manipulation of objects involves a fronto-parietal cortical circuit in the brain, both for monkeys (Hepp-Raymond, Husler, Maier, & Qi, 1994; Kurata & Tanji, 1986; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981; Rizzolatti et al., 1988; Sakata, Taira, & Murata, 1992; Taira, Mine, Georgopoulos, Murata, & Sakata, 1990) and for humans (Binkofski et al., 1999), including ventral premotor cortex (PMv) and the anterior intra-parietal sulcus (AIP). The activation of such a circuit reflects visuomotor transformations that adapt hand shaping to pragmatic object properties. Perception of objects alone also modulates activity of the premotor and parietal areas belonging to this circuit in both non-human primates and humans. In particular, in monkeys, a set of neurons, referred to as canonical neurons, have been shown to respond during the perception of objects which can be manipulated (Murata et al., 1997; Rizzolatti et al., 1988). Using imaging techniques (functional magnetic resonance imaging, fMRI, and positron emission tomography, PET) it has been demonstrated in humans that posterior parietal and premotor areas are activated by object observation (Binkofski, Buccino, Zilles, & Fink, 2004; Grèzes & Decety, 2002; Grèzes, Armony, Rowe, & Passingham, 2003; Grèzes, Tucker, Armony, Ellis, & Passingham, 2003). In sum, the perception of objects which have a pragmatic meaning activate the very system responsible for actual manipulation. This activation would represent the neural counterpart of the Gibson's concept of object affordances (Gibson, 1977, 1979).

Highlighting this relationship between motor activity and pragmatic features or properties/affordances of an object, is the finding that changing physical properties of an object thought to afford action, results in concomitant changes in the motor response to it (Buccino, Sato, Cattaneo, Rodà, & Riggio, 2009), suggesting a coherence between excitability of the motor system and the presence of pragmatic features.

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A special class of manipulable objects are tools. Tools are particularly interesting because beyond being graspable they have an associated function that involves a particular mode of manipulation and use. While in monkeys the use of tools is limited and its generalization to different context very difficult, humans, on the other hand, use tools and understand their meaning (Johnson-Frey, 2003). Several studies have examined neural activity associated with tool processing in humans. A PET study by Grafton, Fadiga, Arbib, and Rizzolatti (1997) showed activation of premotor cortex for viewing of familiar tools; an fMRI study by Chao and Martin (2000) showed activity in PMv for viewing pictures of tools but not for pictures of animals, houses, and faces. An fMRI study by Valyear, Cavina-Pratesi, Stiglick, and Culham (2007) examined activity with presentation of graspable objects, tools, non graspable objects. Greater activity was seen in a specific region of AIPC (Anterior intraparietal cortex), LTOC (left temporo-occipital cortex), IFC (inferior frontal cortex) for tools, but not for other graspable items. In a categorisation of artifacts task, Gerlach, Law, Gade, and Paulson (2002) found left premotor, inferior and middle frontal gyrus activity. Using a task which required subjects to judge whether the way of use, or the purpose/function of use of a pair of tools was the same or not, Canessa et al. (2008) showed left hemisphere activity for the action judgement (way of use) in left PMd (dorsal premotor cortex), IPL (inferior parietal lobule), and IPS (intraparietal sulcus). While many of these studies indicate greater activity in cortical areas that are part of a manipulation network, the most interesting finding is that there is evidence for tool-specific activity in the human parietal cortex (Peeters et al., 2009; Valyear et al., 2007), in a cortical sector that appears to be phylogenetically new (Peeters et al., 2009). The existence of apraxic patients showing a dissociation between conceptual knowledge about tools and the motor skill required to use them (Buxbaum, Sirigu, Schwartz, & Klatzky, 2003; De Renzi, Faglioni, & Sorgato, 1982; Heilman, Rothi, & Valenstein, 1982; Ochipa, Rothi, & Heilman, 1989; Ochipa, Gonzalez Rothi, & Heilman, 1992; Roy, 1985; Sirigu et al., 1995) further suggests that tools are special objects rather than simply manipulable ones.

As we have seen above, the motor system is responsive to the presentation of objects and tools in physical or pictorial form. Does this effect extend to the objects nouns? Until relatively recently, the accepted view of language processing was one involving amodal processing (Fodor, 1975; Mahon & Caramazza, 2005; Pylyshyn, 1984). More recently, especially within the last decade, there has been growing evidence that language understanding requires embodiment (Barsalou, 1999; Fischer & Zwaan, 2008; Gallese & Lakoff, 2005; Glenberg, 1997; Lakoff, 1987; Pulvermüller, 2002; Zwaan & Taylor, 2006; Zwaan, 2004). The essence of the theory of embodiment of language is that understanding of language is achieved by recruiting the same neural systems, sensory and motor, activated when we experience the action or object to which a word refers. Much of the earlier work in this field has focused on verb processing. Electroencephalography (EEG) and fMRI studies, in which subjects had to listen to action verbs, showed activity in the cortical area known to contain the somatotopic representation of the effector involved in performing the action referred to by the verb (Buccino et al., 2001; Hauk, Johnsrude, & Pulvermuller, 2004; Pulvermüller, Harle, & Hummel, 2001; Tettamanti et al., 2005). Furthermore, an overlap within the premotor cortex between sectors recruited by the observation of an action and its corresponding verbal label has been shown (Baumgaertner, Buccino, Ruediger, McNamara, & Binkofski, 2007). Evidence that this motor recruitment occurs early comes from behavioural studies showing a slowing of reaction times when the effector used by the subject to respond is congruent with the presented linguistic material (Boulenger et al., 2006; Buccino et al., 2005; Dalla Volta, Gianelli, Campione, & Gentilucci, 2009; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008). More compelling evidence for an early effect comes from a Transcranial Magnetic Stimulation (TMS) study showing a modulation in the motor evoked potential for a muscle of a given effector associated with the verb presented, when the pulse is applied after the stem of the verb (Buccino et al., 2005). Given the response of the motor system to objects when presented physically or through pictures, one might suggest that modulation should also be evident during noun processing. Little or no evidence exists in relation to this issue. One very recent TMS study has demonstrated the involvement of PMv in the processing of tool words but not of animal words (Cattaneo, Devlin, Salvini, Vecchi, & Silvanto, 2010). While the latter is a very interesting finding and supports our view of the involvement of the motor system in tool noun processing, it does not provide a direct comparison with other object noun categories.

Here we directly compare how the motor system is modulated by nouns referring to objects which are graspable or ungraspable and, at the same time, natural or man-made, the category of graspable man-made objects being tools. We used single pulse TMS applied to the hand area, and the resultant MEP size, to investigate modulation of the motor system when participants are presented with such nouns. The use of TMS allowed us to examine the modulation of the motor system at an early time point. This makes it unlikely that any modulation seen can be explained as a mere side effect of the processing of the language material. We predict that if language is embodied, as previous evidence suggests, then the response of the motor system to nouns from each category should reflect the pattern already seen for the same categories when presented pictorially or physically, i.e. the tool category should be the most effective in modulating the system and we should see an effect of the graspability factor.

2. Methods

2.1. Participants

15 right-handed Italian participants (5 males) took part in the TMS study. Prior to testing subjects gave their informed consent and completed a safety screening questionnaire to rule out any possible contraindications to the method. The age range of participants was 20–27 years. Subjects were compensated for their participation in the study. The work was carried out under ethical permission from the ethical committee of the Medical Faculty at the University of Parma.

2.2. TMS

Excitability of the hand area of the left primary motor cortex was measured using single pulse TMS delivered above the motor hand representation and recording the resultant MEP from the right hand first dorsal interosseous (FDI) muscle.

Participants sat relaxed in a comfortable chair. Electromyographic (EMG) activity of the FDI muscle was recorded. Surface electrodes (Ag-AgCl, disposable, 7 mm × 4 mm) were attached, one on the belly of the FDI muscle (active electrode) and the other on a joint of the pointing finger (reference electrode). Muscle activity was amplified (1000×) and filtered (highpass 0.1 Hz, AC couple, 50 Hz notch) (CED 1902, CED Ltd.). The signal was digitised at a sampling rate of 10 kHz (CED1401 interface, CED Ltd.). Visualisation and later processing was done using Spike2 software (CED Ltd.). Participants wore a swimming cap on the head to allow for accuracy in marking the site for stimulation. TMS was delivered using one module of a Bistim system (Magstim Co. Ltd.) and using a 70 mm figure-of-eight standard coil (Magstim Co. Ltd.). The coil was held tangential to the head. The hand area was first located by stimulation of the contralateral hemisphere until the FDI showed a visible twitch. The subject's threshold was then measured as the level of stimulation required to evoke at least a 50 μV MEP on 5 out of 10 stimulations (Rossini et al., 1994). Stimulation during the task was set to be 120% of the threshold level.

2.3. Stimuli

The set of stimuli (see Appendix A) consisted of four groups of Italian nouns representing: nine manipulable artifacts (e.g., 'martello', 'hammer'), nine manipulable natural objects (e.g., 'fragola', 'strawberry'), nine non-manipulable artifacts (e.g., 'castello', 'castle') and nine non-manipulable natural objects (e.g., 'nuvola', 'cloud'). The noun items were presented visually. All words were three syllables long. The mean number of letters and the mean lexical frequency (in occurrences per million; Laudanna, Thornton, Brown, Burani, & Marconi, 1995 – 3,798,000 words) were 7.67/4.7, 7.44/4.9, 7.00/17.3 and 7.11/10.5 for manipulable artifacts, manipulable natural objects, non-manipulable artifacts and non-manipulable natural