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Parkinson's disease disrupts both automatic and controlled processing of action verbs

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ABSTRACT

The problem of how word meaning is processed in the brain has been a topic of intense investigation in cognitive neuroscience. While considerable correlational evidence exists for the involvement of sensory-motor systems in conceptual processing, it is still unclear whether they play a causal role. We investigated this issue by comparing the performance of patients with Parkinson's disease (PD) with that of age-matched controls when processing action and abstract verbs. To examine the effects of task demands, we used tasks in which semantic demands were either implicit (lexical decision and priming) or explicit (semantic similarity judgment). In both tasks, PD patients' performance was selectively impaired for action verbs (relative to controls), indicating that the motor system plays a more central role in the processing of action verbs than in the processing of abstract verbs. These results argue for a causal role of sensory-motor systems in semantic processing.

1. Introduction

A large body of evidence now supports the view that semantic processes interact in varied ways with the neural systems that underlie perception and motor control. This has led to a number of theoretical proposals, collectively known as the "embodied semantics" framework, according to which the concepts that underlie word meaning are constituted, at least in part, by the memory traces of past sensory-motor experiences. In this view, a word form acquires at least part of its meaning through modality-specific perceptual, emotional, and motor representations, and its retrieval from memory requires the neural re-enactment of these sensory-motor traces (Barsalou, 1999; Binder & Desai, 2011; Damasio, 1989; Gallese & Lakoff, 2005; Kemmerer & Gonzalez-Castillo, 2010; Pulvermüller & Fadiga, 2010).

An alternative view holds that word meaning is fundamentally abstract and modality-independent, and therefore qualitatively distinct from sensory-motor representations (Burgess & Lund, 2000; Fodor, 1975, 2000; Landauer & Dumais, 1997; Pylyshyn, 1999). According to this "disembodied" perspective, all concepts are represented in an abstract and symbolic form. The conceptual system can be indirectly influenced by perception and action (and vice-versa), but the two systems are nevertheless separate and independent. In the following, we will briefly review some of the evidence bearing on this issue, focusing on the relationship between the motor system and the meaning of words referring to actions (action words).

Action concepts offer a convenient test bed for the embodied semantics framework partly because of their strong association with the motor system, such that many of these concepts can be mapped onto well-defined bodily actions, which can be easily measured or induced in the laboratory. Furthermore, the somatotopic organization of the motor cortex allows fine-grained hypotheses about the motor representations underlying different action concepts to be investigated with functional neuroimaging or transcranial magnetic stimulation (TMS). Finally, patients with a variety of motor disorders can be examined for connections between their motor impairments and the abnormal processing of action concepts.

Behavioral evidence supporting a role for motor representations in the processing of action concepts comes mainly from studies showing that exposure to words or sentences interferes with a concomitant or immediately subsequent action in a semantically specific way (Borghi, Glenberg, & Kaschak, 2004; Bub & Masson, 2010; Glenberg & Kaschak, 2002; Myung, Blumstein, & Sedivy, 2006; Zwaan & Taylor, 2006; see Fischer & Zwaan, 2008, for a review). Glenberg and colleagues, for instance, found that when participants make semantic judgments about sentences that imply a motion toward or away from the body, responses are faster when they require a movement in the same direction as that implied in the sentence (action-sentence compatibility effect). Other studies indicate that this interaction between language and action is also

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body-part specific (Scorolli & Borghi, 2007) and happens very early following word presentation (within 200 ms; Boulenger et al., 2006; Nazir et al., 2008; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008).

Additional evidence comes from several studies showing that motor cortical areas are selectively activated during processing of action-related words and sentences (for reviews, see Aziz-Zadeh & Damasio, 2008; Fernandino & Iacoboni, 2010; Kemmerer & Gonzalez-Castillo, 2010). Some functional MRI studies suggest that verbs related to different body parts (e.g. hand, foot, or mouth) activate the primary motor and the premotor cortex on the left hemisphere in roughly somatotopic fashion, consistent with the idea of motor simulation (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Boulenger, Hauk, & Pulvermüller, 2009; Hauk, Johnsrude, & Pulvermüller, 2006; Raposo, Moss, Stamatakis, & Tyler, 2009; Tettamanti et al., 2005). Other studies have shown increased activation in the anterior supramarginal gyrus, which is involved in the control of goal-directed actions, for processing of action-related words or sentences, compared to non-action related stimuli (Desai, Binder, Conant, Mano, & Seidenberg, 2011; Desai, Binder, Conant, & Seidenberg, 2010; Noppeney, Josephs, Kiebel, Friston, & Price, 2005; Rueschemeyer, Van Rooij, Lindemann, Willems, & Bekkering, 2010; Tettamanti et al., 2005). Further evidence of motor cortex activation during action language processing comes from studies employing TMS-induced motor-evoked potentials (Buccino et al., 2005; Glenberg, Sato, Cattaneo, Riggio, et al., 2008; Oliveri et al., 2004), EEG (Hauk & Pulvermüller, 2004; van Elk, van Schie, Zwaan, & Bekkering, 2010), and MEG (Boulenger, Shtyrov, & Pulvermüller, 2012; Pulvermüller, Shtyrov, & Ilmoniemi, 2005).

As pointed out by skeptics (e.g. Bedny & Caramazza, 2011; Chatterjee, 2010; Mahon & Caramazza, 2008), these studies have not directly demonstrated that motor representations play a *causal role* in language comprehension. In fact, a crucial prediction of embodied theories of meaning is that disruption of the motor system should selectively disrupt processing of action-related concepts. Preliminary evidence in line with this prediction has been provided by TMS studies and by studies of neurological patients.

Pulvermüller et al. (2005) found that single-pulse TMS over the left primary motor hand area led to faster lexical decision responses to arm-related than to leg-related action words, while stimulation over the leg area produced the opposite result. Similarly, Papeo, Vallesi, Isaja, and Rumiati (2009) found that stimulation over the hand motor area induced an RT advantage for hand-action verbs over non-hand-action verbs, although this effect was present only when stimulation was delayed by 350 ms relative to word onset. When the pulse was delivered at 170 ms post-stimulus onset (similar to the timing used by Pulvermüller et al., 2005), no differences between the two word types were observed. Tomasino, Fink, Sparing, Dafotakis, and Weiss (2008) found that single-pulse TMS over the motor hand area led to facilitation of action verb processing (relative to stimulation over the vertex) when participants were required to produce motor imagery in response to the verb, but not when making frequency judgments or simply reading the word. Unfortunately, since participants were tested only on action verbs in this study, it is not possible to conclude that this effect was specific to action words. Finally, a study by Willems, Labruna, D'Esposito, Ivry, and Casasanto (2011) found that theta-burst stimulation (TBS) over the left premotor cortex facilitated processing of manual-action verbs, but not of non-manual-action verbs, in a subsequent lexical decision task. The neurophysiologic effects of single-pulse TMS and TBS are still not fully understood, but to the extent that the behavioral effects in these studies were specific to action verbs, the TMS evidence generally supports an involvement of the motor system in action-verb processing.

Studies of neurological patients can provide more direct evidence for the necessity of the motor system in processing action concepts. Brain systems involved in motor control can be disrupted either by focal brain lesions, such as those resulting from stroke, or by neurodegenerative disorders, such as amyotrophic lateral sclerosis (ALS; also known as motor neuron disease) and Parkinson's disease. Several studies suggest that both types of disruption lead to deficits in action semantics. For instance, Buxbaum and Saffran (2002) tested a group of chronic stroke patients – half of them presenting with apraxia – on tasks requiring semantic similarity judgments. They found that apraxic patients were more impaired at reasoning about tools than about animals, and also more impaired at judging tool manipulation than tool function, while non-apraxic patients showed the opposite pattern. Furthermore, apraxics performed worse than non-apraxics in reasoning about body parts. Convergent results were reported by Neininger and Pulvermüller (2003), who showed that patients with right frontal lesions (and associated left hemiparesis) were selectively impaired at processing action verbs, whereas patients with right temporo-occipital lesions were more impaired at processing visual nouns.

Similar results were found with ALS patients. Bak, O'Donovan, Xuereb, Boniface, and Hodges (2001), using a word-picture matching task, showed that these patients were more impaired at matching action verbs than concrete nouns, while Alzheimer's patients and healthy controls showed no difference between these two categories. The same pattern of impairment was obtained in a study of a familial form of movement disorder resembling progressive supranuclear palsy (Bak et al., 2006). Moreover, a recent study by Grossman et al. (2008) found that not only were ALS patients impaired on action semantics, relative to object semantics, but the degree of cortical atrophy in motor and premotor areas correlated with performance on action-verb judgments (and not on judgments of concrete nouns).

Parkinson's disease (PD) is another neurodegenerative disorder that severely affects the motor system. It is characterized by rigidity, bradykinesia (slowness of movement), postural instability, and tremor during rest, resulting from progressive loss of dopaminergic cells in the substantia nigra (for a review, see Dauer & Przedborski, 2003). Patients can also present with cognitive impairments, particularly deficits in executive functions, which may be related to dysfunction of the frontostriatal circuitry (Koerts, Leenders, & Brouwer, 2009; Owen, 2004; Zgaljardic, Borod, Foldi, & Mattis, 2003).

The effects of the disruption of the dopaminergic pathways on the various cortical regions are not fully understood, but the motor symptoms of PD have been linked to abnormal activity in the primary motor cortex (M1) and the supplementary motor area (SMA) (Jenkins, Fernandez, Playford, et al., 1992; Pasquereau & Turner, 2011; Rascol et al., 1992; Suppa, Iezzi, Conte, et al., 2010; Wu et al., 2011). Thus, while PD certainly does not represent a case of "pure" motor cortex dysfunction, it presents an opportunity to test the integrity of the conceptual system in the face of a disruption of those components of the motor network.

Boulenger, Mechtouff, et al. (2008) pursued this goal by testing PD patients and healthy controls with a lexical decision (LD) task and masked priming. Target words were either action verbs or concrete nouns, and they were primed by either the same word (displayed in capitalized letters) or by a sequence of consonants. They found that off-medication PD patients displayed reduced priming for action verbs relative to concrete nouns, compared to healthy controls or to the same patients on medication. Since the prime was not consciously perceived by the participants, this result suggests that motor simulations are automatically activated by action word recognition, in the absence of explicit semantic processing. Another study by Cotelli et al. (2007) showed that PD patients also perform worse in action naming than in object