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Dissociation and association of the embodied representation of tool-use verbs and hand verbs: An fMRI study

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ABSTRACT

Embodied semantic theories suppose that representation of word meaning and actual sensory-motor processing are implemented in overlapping systems. According to this view, association and dissociation of different word meaning should correspond to dissociation and association of the described sensory-motor processing. Previous studies demonstrate that although tool-use actions and hand actions have overlapping neural substrates, tool-use actions show greater activations in frontal–parietal–temporal regions that are responsible for motor control and tool knowledge processing. In the present study, we examined the association and the dissociation of the semantic representation of tool-use verbs and hand action verbs. Chinese verbs describing tool-use or hand actions without tools were included, and a passive reading task was employed. All verb conditions showed common activations in areas of left middle frontal gyrus, left inferior frontal gyrus (BA 44/45) and left inferior parietal lobule relative to rest, and all conditions showed significant effects in premotor areas within the mask of hand motion effects. Contrasts between tool-use verbs and hand verbs demonstrated that tool verbs elicited stronger activity in left superior parietal lobule, left middle frontal gyrus and left posterior middle temporal gyrus. Additionally, psychophysiological interaction analyses demonstrated that tool verbs indicated greater connectivity among these regions. These results suggest that the brain regions involved in tool-use action processing also play more important roles in tool-use verb processing and that similar systems may be responsible for word meaning representation and actual sensory-motor processing.

1. Introduction

The brain mechanism of word meaning is an important topic that has attracted increasing attentions. Embodied semantic theories claim that word meaning is grounded in sensory-motor systems (Barsalou, 1999; Glenberg, 1997; Pulvermüller, 2005). This opinion is supported by neuroimaging studies, which reveal that reading or listening to words can activate sensory-motor regions that enact the word meaning. For instance, color knowledge processing induced by color words can elicit activations in color perceiving areas in fusiform gyrus (FG) (Pulvermüller & Hauk, 2006; Simmons et al., 2007). Moreover, numerous studies indicate that viewing verbs that describe actions of different body parts (such as *pick*, *lick* and *kick*) can elicit effects in motor and premotor areas in a somatotopic way (Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, Härle, & Hummel, 2001; Raposo, Moss, Stamatakis, & Tyler, 2009). These results support the view that neurons responsible for sensory-motor information and word forms strongly link to each other (Pulvermüller, 2001) or the view that language comprehension is mediated by implicit sensory-motor simulation (Barsalou, 1999; Glenberg & Kaschak, 2002). The findings of motor and premotor activation are extended from the processing of single verbs to the processing of phrases, sentences and even figurative language that contain body-schema verbs (Aziz-Zadeh, Wilson, Rizzolatti, & Iacobonni, 2006; Boulenger, Hauk, & Puvermüller, 2009; Tettamanti et al., 2005; but see Raposo et al., 2009). However, for verbs that depict complex actions, such as tool-use action verbs (tool verbs for short), whether their meaning is ground in sensory-motor systems, and what difference between their meaning and the meaning of hand verbs are still unclear (Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008; Tyler et al., 2003).

As a defining characteristic of humans, tool-use introduces challenges on motor skill and tool knowledge compared with hand actions without tools. This is because the goal of tool-use is not enhancing movements of the upper limbs, but implementing qualitatively different mechanical actions (Frey, 2007). Such extra requirements are demonstrated by recent neuroimaging studies, which find that tool-use processing elicits stronger effects than hand action processing in both dorsal (frontal–parietal) stream

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and ventral (posterior temporal) stream (Frey, 2008). The dorsal stream is mainly responsible for motor skill processing in tool-use. Left superior parietal lobule and inferior parietal lobule (SPL and IPL) are responsible for tool-use motor skill planning (Chaminade, Meltzoff, & Decety, 2005; Choi et al., 2001; Fridman et al., 2006; Goldenberg & Hagmann 1998; Johnson-Frey, Newman-Norlund, & Grafton, 2005). Left middle frontal gyrus (MFG) and inferior frontal gyrus (IFG, BA 44/45) are responsible for integrating the actor's prospective goals (Buccino et al., 2004; Duncan & Owen, 2000; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). The ventral stream is responsible for tool information processing. The medial FG is responsible for tool shape processing (Beauchamp, Lee, Haxby, & Martin, 2002; Mahon et al., 2007), and the left posterior middle temporal gyrus (MTG) is responsible for tool knowledge processing (Damasio et al., 2001; Mahon et al., 2007; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Martin, Wiggs, Ungerleider, & Haxby, 1996). In a word, these studies indicate that although tool-use actions and hand actions have overlapping neural substrates, tool-use shows greater activations in frontal, parietal and posterior temporal regions that are responsible for action goal integration, motor-skill planning and tool knowledge processing.

According to the embodied semantic view, the representation of word meaning and actual sensory-motor processing are implemented in overlapping systems. If this is true, the association and the dissociation of different word meaning should correspond to the association and the dissociation of the described sensory-motor processing. Thus, we hypothesize that (1) reading tool verbs and hand verbs should elicit common activity in hand motion areas and (2) tool verbs and hand verbs should elicit different effects in tool-use related regions, such as IFG (BA 44/45), MFG, SPL/IPL, medial FG and left posterior MTG. However, previous studies about tool verbs have not indicated clear findings about the two above hypotheses. For example, Tyler et al. (2003) used a semantic categorization task and found that tool verbs (such as *drilling*) and biological verbs (such as *swimming*) showed similar frontal–temporal activities and no difference was found. With a semantic similarity judgment task, Kemmerer et al. (2008) found that biological verbs (such as *running*) and tool verbs (such as *cutting*) elicited similar effects in frontal–temporal areas, in addition the tool verbs elicited activation in left angular gyrus (AG). However, the study did not directly compare the tool verbs with the biological verbs. Thus, it is still unclear whether the regions responsible for tool-use functions are more involved in tool verb processing, i.e. whether tool verbs elicit stronger effects than hand verbs in areas of left SPL/IPL, left MFG/IFG (BA 44/45) and left posterior MTG.

One possible reason for the difficulty of seeing the involvement of tool-use network in reading tool verbs may be that the tool-use network contains much more information compared with biological motions, and that tool-use occurs much later than biological actions in the history of human evolution and ontogenetic development. Thus, the combination between the word form and the tool-use network might be relatively vulnerable and easily disturbed. To investigate whether the tool-use network engages in the semantic representation of tool verbs, both the elaborate semantics specifying the manners of how hand interacts with tools and the strong association between word form and word meaning may be necessary. In the current study, we used single-character Chinese action verbs, which emphasize on very specific manual action manner and refer to a limited range of actions. As a typical ideographic writing system, Chinese written word forms have strong connections with word meaning. For instance, many single-character words have semantic radicals in their word forms to indicate meaning (Zhang & Chen, 2008). Most of single-character hand verbs contain a hand-related semantic radical, such as *nie* (*pinch*) (Fig. 1A). Single-character tool verbs can be divided into two types based on their semantic radicals (Zhang & Chen, 2008).

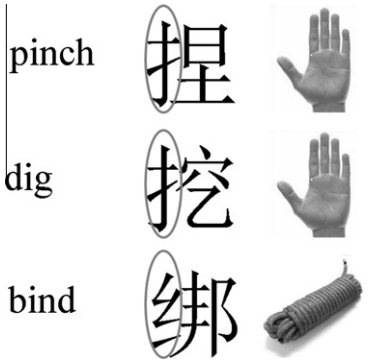

Fig. 1. Examples of experimental stimuli. Circles indicate the semantic radicals. Top line: an example of Chinese hand verbs, its English translation equivalent, and a picture indicating the hand semantic radical. Middle line: an example of Chinese tool verbs (hand part), its English translation equivalent, and a picture indicating the hand semantic radical. Bottom line: an example of Chinese tool verbs (tool part), its English translation equivalent, and a picture indicating the tool semantic radical.

In one type, each tool verb contains a hand-related semantic radical, such as *wa* (dig) (Fig. 1B). In the other type, each tool verb contains a tool-related semantic radical, such as *bang* (bind, here stresses the rope) (Fig. 1C). To examine the semantic representation differences between tool verbs and hand verbs thoroughly, both types of tool verbs were compared with hand verbs in the present study. A passive reading task was used to avoid confounding from motor response and to investigate the automatic access from word form to word meaning (Aziz-Zadeh et al., 2006; Hauk et al., 2004). A hand motion task was conducted after the passive reading task to localize hand motor areas and to examine whether hand verbs and tool verbs elicit effects in hand motor areas (Aziz-Zadeh et al., 2006; Hauk et al., 2004; Raposo et al., 2009). To explore the differences between functional connectivity of tool verbs and hand verbs, psychophysiological interaction analyses (PPI, Friston et al., 1997) were performed based on the contrasts between tool verbs and hand verbs. We predict that all verbs show common activations in hand motion areas within the mask of hand motion effects. The tool verbs (hand part) may reveal stronger effects in areas of SPL/IPL and MFG/IFG (BA 44/45) that play roles in motor-skill planning and action goal integration, because the semantic radicals emphasize hand motion. The tool verbs (tool part) may reveal stronger effects in area of left posterior MTG that is responsible for tool information, because the semantic radicals stress tool involvement.

2. Material and methods

2.1. Participants

Twenty healthy Chinese volunteers (13 females, age range 19–28 years) participated in the fMRI study after completing the informed consent form approved by the Imaging Center for Brain Research of Beijing Normal University. They all had normal or corrected to normal vision and reported no history of neurological or psychiatric disorder. All participants were right-handed according to a modified Chinese version of the Edinburgh Handedness Inventory (Oldfield, 1971).

2.2. Materials

At first, 120 regular single-character Chinese transitive verbs (hand verbs and tool verbs) were selected from Xin Hua Dictionary (The Commercial Press, 2006). Noun–verb homophones were excluded. Twenty native Chinese speakers (none of them took part in the fMRI study) rated the familiarity, concreteness and