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Effects of motion speed in action representations

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ABSTRACT

Grounded cognition accounts of semantic representation posit that brain regions traditionally linked to perception and action play a role in grounding the semantic content of words and sentences. Sensory-motor systems are thought to support partially abstract simulations through which conceptual content is grounded. However, which details of sensory-motor experience are included in, or excluded from these simulations, is not well understood. We investigated whether sensory-motor brain regions are differentially involved depending on the speed of actions described in a sentence. We addressed this issue by examining the neural signature of relatively fast (*The old lady scurried across the road*) and slow (*The old lady strolled across the road*) action sentences. The results showed that sentences that implied fast motion modulated activity within the right posterior superior temporal sulcus and the angular and middle occipital gyri, areas associated with biological motion and action perception. Sentences that implied slow motion resulted in greater signal within the right primary motor cortex and anterior inferior parietal lobule, areas associated with action execution and planning. These results suggest that the speed of described motion influences representational content and modulates the nature of conceptual grounding. Fast motion events are represented more visually whereas motor regions play a greater role in representing conceptual content associated with slow motion.

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1. Introduction

Recent theories of human cognition argue for a tight coupling between perceptual and representational systems. Proposals differ from each other in the exact role they ascribe to perceptual and motor brain regions in conceptual representation (for a review see: Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012), but they all share the notion that sensorimotor experiences subserve cognition. On this view, experiential traces stored in sensorimotor brain regions can provide a means for grounding lexical-semantic content (Barsalou, 2008; Glenberg, 1997; Pulvermüller, 1999).

Several lines of evidence support the grounded cognition view. Behavioral studies have provided evidence that language comprehension shares computational processes with perception and action (for reviews see Fischer & Zwaan, 2008; Zwaan & Kaschak, 2008). Similarly, neuroimaging studies have provided evidence that language comprehension involves the recruitment of sensory-motor brain regions. Several studies have shown that the comprehension of action verbs (Hauk, Johnsrude, & Pulvermüller, 2004; Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008; Van Dam, Rueschemeyer, & Bekkering, 2010), action sentences (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Desai, Binder, Conant, Mano, & Seidenberg, 2011; Desai, Binder, Conant, & Seidenberg, 2009; Desai, Conant, Binder, Park, & Seidenberg, 2013; Tettamanti et al., 2005) and words denoting manipulable objects (Chao & Martin, 2000; Rueschemeyer, Van Rooij, Lindemann, Willems, & Bekkering, 2010; Saccuman et al., 2006) reliably activate the cerebral motor system. In a similar vein, neuroimaging studies have provided evidence that comprehension of words semantically related to color (Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Simmons et al., 2007), odor (Gonzalez et al., 2006) and audition (Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008), draw on brain regions relevant for coding corresponding modalities (see Binder & Desai, 2011 for a review).

A number of studies on patients with motor impairments corroborate these findings. In two studies with Parkinson's patients, Fernandino et al. (2012, 2013) showed that patients (in contrast to controls) were selectively impaired in automatic and controlled processing of action verbs and sentences. Neininger and Pulvermüller (2003) showed that patients with predominant right

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frontal lesions were impaired in processing of action verbs, whereas patients with right temporo-occipital lesions showed impairments in processing nouns with strong visual associations. Trumpp, Kliese, Hoenig, Haarmeier, & Kiefer (2013) showed that damage to the left auditory association cortex led to selective impairments in the processing of sound-related concepts (e.g., "*bell*"). Bonner and Grossman (2012) demonstrated that reduced gray matter density in patients with auditory association cortex atrophy was correlated with the severity of their deficit in processing sound-related words. Desai, Herter, Riccardi, Rorden, and Fridriksson (2015) showed that the degree of selective impairment in comprehension accuracy of action-related words was predicted by the degree of impairment in reaching performance in a group of chronic stroke patients. These findings provide strong evidence for a role of sensory-motor brain regions in language comprehension.

Despite the fact that numerous studies have reported sensory-motor activations in conjunction with language, the exact nature of these activations remains unclear. Activation that was specific to the semantic category presented has been documented as early as ~200 ms after word onset (Hauk & Pulvermüller, 2004; Pulvermüller, Härle, & Hummel, 2000), when subjects did not attend to a word (Pulvermüller & Shtyrov, 2006; Shtyrov, Hauk, & Pulvermüller, 2004) and for action verbs embedded within abstract sentences (Boulenger, Hauk, & Pulvermüller, 2009). These findings have been taken to support the notion that embodied lexical-semantic effects are automatic and invariant. Recent studies, however, have provided evidence that the overlap observed in modality-specific sensory-motor processing and conceptual processing depends on contextual constraints (Hoenig, Sim, Bochev, Herrnberger, & Kiefer, 2008; Kalénine, Mirman, Middleton, & Buxbaum, 2012; Lee, Middleton, Mirman, Kalénine, & Buxbaum, 2013; Van Dam, Van Dijk, Bekkering, & Rueschemeyer, 2012; Yee & Thompson-Schill, 2016). The interaction between modality-specific sensory-motor regions and conceptual areas might even be more intricate. It is generally assumed that overlap in the computational mechanisms that underlie conceptual and sensory-motor processing reflect bottom-up sensory-motor effects on higher-order cognition. However, factors like language-mediated categories can constrain sensory perception (Brouwer & Heeger, 2013; Lee & Noppeney, 2014; Puri, Wojciulik, & Ranganath, 2009), suggesting that shared computational processes might partially reflect top-down effects of linguistic priors on perception (Simanova, Francken, de Lange, & Bekkering, 2016).

Another crucial issue in theories of embodiment concerns the precise nature of conceptual grounding. Which details of sensory-motor experience are included in, or excluded from these simulations? Several studies have provided evidence that the sensory-motor information activated during language comprehension is fairly specific in nature. Mental simulations seem to encode effector-specific information (Hauk et al., 2004; Scorolli & Borghi, 2007), the amount of detail in which movement kinematics are specified by a verb (e.g., *to wipe* vs. *to clean*: Van Dam et al., 2010), the directionality of the action an object affords (Rueschemeyer, Pfeiffer & Bekkering, 2010; Zwaan & Taylor, 2006), implied orientation of an object (Zwaan, Stanfield, & Yaxley, 2002), part of the visual field where a described scene would take place (Bergen, Lindsay, Matlock, & Narayanan, 2007; Richardson, Spivey, Barsalou, & McRae, 2003) and direction of motion (Zwaan, Madden, Yaxley, & Aveyard, 2004). For example, Zwaan, Madden, Yaxley, and Aveyard (2004) had participants decide whether two sequentially presented visual objects were identical or not, while concurrently listening to sentences that implied a movement in a certain direction. Crucially, either the first or second object would be depicted larger and therefore suggesting motion of the object towards or away from the observer. Participants were faster to respond if the direction of the movement implied by the sentence matched the direction suggested by the sequence in which the two pictures were presented. These findings provide evidence that language-induced perceptual and motor simulations contain at least some details about objects and the actions they afford.

The abovementioned demonstrations of strong overlap in the computational mechanisms that underlie conceptual and sensory-motor processing lay at the core of any grounded cognition account. There has also been acknowledgment of the necessity of some degree of abstraction away from sensory-motor processes (Binder, 2016; Barsalou, 2016; Binder & Desai, 2011), and concepts are therefore not entirely reducible to modality-specific sensory or motor representations. In order for a grounded cognition account to be successful and move forward, it is important to detail in which exact ways sensory and motor representations contribute to language processing. Interesting open questions are: How extensive is the overlap in neural pathways involved in modality-specific sensory-motor processing and conceptual processing? Is detailed information incorporated more from certain sensory-motor modalities than others during language-induced simulations?

The role that abstraction away from detailed sensory-motor information plays in sensory-motor grounding can provide us with viable insights in this regard. The mechanism of abstraction might be able explain why in many instances conceptual processing is similar to but does not equate with sensory-motor processing. Hsu et al. (2011) demonstrated that the extent to which primary perceptual regions were activated in a color judgment task depended on the degree of perceptual resolution needed by the task. If the task context required retrieval of detailed color knowledge the neural response was highly similar to that observed in color perception, the response in color perception regions was significantly reduced if the task could be accomplished on the basis of categorical (abstracted) knowledge. On the basis of these types of findings, several authors have proposed that conceptual knowledge may be represented at multiple levels of abstraction (Binder & Desai, 2011; Thompson-Schill, 2003). In this view, conceptual processing draws heavily on association areas involved in integration and abstraction in addition to utilizing sensory-motor representations to flesh out particular concepts (Binder, 2016; Simmons & Barsalou, 2003). As detailed above, task and linguistic context are likely important factors in determining the extent to which sensory-motor processes are recruited during conceptual processing, and therefore the extent to which representations and simulations mirror objects, actions and events in the real world (see also Hoenig et al., 2008; Van Dam et al., 2012 on the related topic of conceptual flexibility).

An interesting topic in this regard is (1) whether a relatively fine-grained parameter of an action like movement speed is incorporated in language-induced perceptual and motor simulations, and if so, (2) what exact information is activated. Behavioral studies have provided ample evidence that mental simulations during language processing are affected by the motion dynamics of the motor experiences on which they are based. Meteyard, Bahrami, and Vigliocco (2007), for example, showed that listening to verbs that denoted upward or downward motion affected perceptual sensitivity to motion, performance in a motion-detection task and subject's internal decision criteria. Futhermore, recent behavioral studies have indicated mental simulations for speed during language processing. In a recent study, Speed and Vigliocco (2014) had participants listen to sentences describing fast and slow actions (e.g., *The lion dashed to the balloon* vs. *The lion ambled to the balloon*). They found that participants showed slower eye movements and longer looking times towards a concurrent visual scene while listening to slow actions as compared to fast actions. Lindsay, Scheepers, and Kamide (2013) presented participants with

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