Acta Psychologica xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Time course of action representations evoked during sentence comprehension

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ARTICLE INFO

Article history:
Received 11 May 2013
Received in revised form 10 January 2014
Accepted 30 January 2014
Available online xxxx

PsycINFO classification:
2340 (cognitive processes)

Keywords:
Action representations
Eye movements
Imagery
Mental simulation
Motor resonance
Sentence comprehension

ABSTRACT

The nature of hand-action representations evoked during language comprehension was investigated using a variant of the visual–world paradigm in which eye fixations were monitored while subjects viewed a screen displaying four hand postures and listened to sentences describing an actor using or lifting a manipulable object. Displayed postures were related to either a functional (using) or volumetric (lifting) interaction with an object that matched or did not match the object mentioned in the sentence. Subjects were instructed to select the hand posture that matched the action described in the sentence. Even before the manipulable object was mentioned in the sentence, some sentence contexts allowed subjects to infer the object's identity and the type of action performed with it and eye fixations immediately favored the corresponding hand posture. This effect was assumed to be the result of ongoing motor or perceptual imagery in which the action described in the sentence was mentally simulated. In addition, the hand posture related to the manipulable object mentioned in a sentence, but not related to the described action (e.g., a writing posture in the context of a sentence that describes lifting, but not using, a pencil), was favored over other hand postures not related to the object. This effect was attributed to motor resonance arising from conceptual processing of the manipulable object, without regard to the remainder of the sentence context.

1. Introduction

Substantial evidence supports the proposal that mental representations of actions are evoked during language comprehension (e.g., Glenberg & Kaschak, 2002; Kaschak & Borreggine, 2008; Zwaan & Taylor, 2006). These representations may support an active, deliberate mental simulation of motor activity described in a sentence, which in turn could contribute to successful comprehension. In addition, an action representation may become active when an object is mentioned simply by virtue of its inclusion in the general conceptual knowledge associated with that object (e.g., Bub & Masson, 2012; Masson, Bub, & Lavelle, 2013). This elicitation of action representations may be quite separate from any ongoing, overtly constructed mental simulation and may result merely from identifying or holding in working memory an object concept. We report an experiment that provides evidence consistent with this distinction between two different roles played by action representations during comprehension.

Both neuroimaging and behavioral evidence support the view that action representations are evoked during language comprehension when the message conveys information about manipulable objects. Research using fMRI has shown that when listening to action-based verbs, or nouns representing manipulable objects, activation of somatotopically relevant areas of motor cortex occurs (Rueschemeyer, Brass, & Friederici, 2007; Tettamanti et al., 2005). Activations of this kind are also found during actual performance of actions described by sentences (Hauk, Johnsrude, & Pulvermüller, 2004). This evidence indicates that during the processing of words that denote manipulable objects or actions, the motor cortex creates an embodied representation that may then become reactivated upon reencountering that event. Behavioral evidence for a relationship between language comprehension and embodied action representations includes demonstrations that reach and grasp responses can be made more quickly when cued in the context of sentences that describe related as opposed to unrelated actions (e.g., Bub & Masson, 2010; Masson, Bub, & Newton-Taylor, 2008; Masson, Bub, & Warren, 2008; Masson et al., 2013).

It has been suggested that embodied representations of action are a form of mental simulation, and that it is possible to differentiate two distinct types of mental simulation, which we will refer to as *motor imagery* and *motor resonance* (Barsalou, 2008; Kent & Lamberts, 2008; Moulton & Kosslyn, 2009). Moreover, there is neuroimaging evidence that supports a dissociation between these two mechanisms (Willems, Toni, Hagoort, & Casasanto, 2010). Motor imagery is the explicit construction of mental representations of action in working memory and these representations may be maintained indefinitely (Grezes & Decety, 2001; Jeannerod, 1994). We intend this term to include the possibility that instead of motor-based imagery a mental simulation may involve perceptual imagery representing visible aspects of action (e.g., a mental image of a moving hand). In contrast, motor resonance

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http://dx.doi.org/10.1016/j.actpsy.2014.01.017

is an automatic recruitment of an action representation that usually is temporally localized to the presentation of an inducing stimulus rather than extending over time periods typical of motor imagery (Masson et al., 2013; Zwaan & Taylor, 2006). For example, Zwaan and Taylor had subjects read sentences one segment at a time, with segments advancing as subjects rotated a knob. The required rotation was either clockwise or counterclockwise and that direction was either consistent or inconsistent with the action implied by the verb in the sentence (e.g., closing or opening a bottle). Reading time was influenced by the consistency between the verb and the direction of rotation, but this influence was restricted to the sentence frame containing the verb and did not extend beyond that. Similarly, Masson et al. cued subjects to perform a reach and grasp response while listening to a sentence that described an action that was congruent or incongruent with respect to the cued action. Congruency effects on action responses were obtained when the action cue was presented during or shortly after mention of a manipulable object in the sentence. When the action was cued later in the sentence, the congruency effect had dissipated. Masson et al. also showed, however, that if subjects were induced to engage in motor imagery during presentation of the sentence (by requiring subjects to be prepared to pantomime the action described in the sentence), the congruency effect on action performance was sustained through to the end of the sentence.

An additional finding in one of the motor imagery experiments reported by Masson et al. (2013, Exp. 6) was that a cued action relevant only to the manipulable object mentioned in a sentence, but not to the particular action being described, was primed along with the action that fully conformed to the sentence context. For instance, given the sentence

(1) *To clear the shelf, Jack lifted the pen*

the action that is congruent with the full context is a horizontally oriented precision grip. That action was primed by the sentence context, but so, too, was the action corresponding to using a pen (a writing posture), even though writing was not implied by the sentence context as a whole, only by the specific manipulable object mentioned in the sentence. Masson et al. proposed that priming of the lifting action was associated with overt mental simulation of the action described in the sentence context, and that priming of the functional action (writing in this example) resulted from motor resonance induced by mention of the manipulable object.

In the experiment reported here, we sought to examine this proposed distinction using a new method that was intended to provide a fine-grained assessment of the time course of these two mechanisms for invoking action representations. Our approach is an adaptation of the visual–world paradigm, which uses tracking of eye movements and fixations to provide a real-time assessment of the knowledge representations that are active during language processing. Research using this paradigm most often analyzes the likelihood with which a subject fixates a particular image or object over time when that item is presented as one member of an array of stimuli (e.g., Huettig, Rommers, & Meyer, 2011). Past research has shown that subjects' eyes tend to fixate on stimuli that are congruent with current mental operations, providing researchers with information about the time course of mental processes during language comprehension (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995).

With this method, we have a means of probing the status of action representations without requiring subjects to execute reach and grasp actions. Rather than cuing subjects to perform hand actions at various points during the presentation of a sentence context, we had them view a display of four hand postures. Two of the postures were relevant to the manipulable object mentioned in the context sentence, one representing what we refer to as a *volumetric* action (used to move or pick up an object), and the other corresponding to a *functional* action (performed when using the object for its intended purpose). The sentence described either a volumetric or a functional interaction with the object, so only one of these two postures fits the full sentence context. For example, the following sentence fits the functional action of pressing buttons rather than the volumetric action of lifting the device:

(2) *Bobby used the cellphone to text his friends.*

The other two postures in a display depicted the functional and volumetric actions associated with an object not mentioned in the sentence.

To encourage the generation of overt mental simulation of the activity described by sentence contexts, subjects were instructed to select the depicted hand posture that matched the action described by the sentence context. We assumed that if motor representations corresponding to an action afforded by the manipulable object mentioned in the sentence were evoked, then the subject's eyes would tend to move to the displayed posture that depicted that action. Under the instruction to select the hand posture that fits the sentence context, eye fixations should eventually be heavily concentrated on the relevant posture. The eye-tracking method we used allows us to ask when, during the course of sentence processing, particular action representations are elicited. For example, constructing a mental simulation of a described action may be postponed until the target object is mentioned. Alternatively, mental simulation may begin as soon as sentence information provides some constraints on the set of possible actions that fit with what has been presented so far. Consider the following two sentences, in which the action's distal goal (outlining a pattern) is presented early versus late:

(3) *To outline her pattern, Grace used the marker.*
(4) *Grace used the marker to outline her pattern.*

When the distal goal is mentioned first, as in (3), some constraints on the possible relevant actions are established in the first clause of the sentence and construction of a mental simulation may begin at a relatively early stage during sentence comprehension. But when mention of the distal goal is moved to the end of the sentence, as in (4), few if any constraints on the relevant action are present until the verb or perhaps even the manipulable object is mentioned.

Of particular interest in this experiment is the possible role played by motor resonance. Masson et al. (2013) demonstrated that an action representation relevant to a manipulable object mentioned in a context sentence was primed, even though it was not consistent with the specific action described by the sentence. Mention of an object by itself seems capable of evoking both functional and volumetric action representations (e.g., Bub & Masson, 2012). This type of activation appears to be a product of motor resonance elicited as part of the general knowledge associated with a manipulable object. Either functional or volumetric action representations may be elicited through this mechanism when the context consists only of the name of an object (Bub & Masson, 2012), but it is not clear whether this principle holds when a complete sentence context specifying a particular action is presented. Masson et al. (Exp. 6) showed that functional action representations were elicited through motor resonance when sentence contexts described volumetric interactions with objects and subjects were induced to overtly simulate those interactions, but they did not test the converse possibility (volumetric actions elicited when subjects apply motor imagery to a functional action). Moreover, their method required subjects to execute overt reach and grasp actions. These response demands may have influenced the pattern of motor activations that were observed. In the present experiment, we sought evidence for evocation of action representations when subjects were not explicitly making reach and grasp actions. It is important to note that the evidence for motor resonance that we anticipate finding would mean that an action representation inconsistent with the general sentence context, but congruent with the manipulable object mentioned in the sentence, would be evoked and that this would happen at the same time as the fully congruent action representation was highly active as part of an overt mental simulation of the activity described by the sentence context. The onset of

Please cite this article as: Heard, A.W., et al., Time course of action representations evoked during sentence comprehension, *Acta Psychologica* (2014), http://dx.doi.org/10.1016/j.actpsy.2014.01.017