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Alive and grasping: Stable and rapid semantic access to an object category but not object graspability

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ABSTRACT

How quickly do different kinds of conceptual knowledge become available following visual word perception? Resolving this question will inform neural and computational theories of visual word recognition and semantic memory use. We measured real-time brain activity using event-related brain potentials (ERPs) during a go/nogo task to determine the upper limit by which category-related knowledge (living/nonliving) and action-related knowledge (graspable/ungraspable) must have been accessed to influence a downstream decision process. We find that decision processes can be influenced by the living/nonliving distinction by 160 ms after stimulus onset whereas information about (one-hand) graspability is not available before 300 ms. We also provide evidence that rapid access to category-related knowledge occurs for all items, not just a subset of living, nonliving, graspable, or ungraspable ones, and for all participants regardless of their response speed. The latency of the N200 nogo effect by contrast is sensitive to decision speed. We propose a tentative hypothesis of the neural mechanisms underlying semantic access and a subsequent decision process.

Introduction

Millions of years of evolution have endowed a wide variety of organisms with peripheral and central nervous systems capable of acquiring, retaining, and retrieving knowledge about perceptible objects in their environment. However, only literate humans can rely on the indirect path to meaning (semantic access) from written language. Upon visually perceiving an inherently arbitrary symbol like “dolphin”, “dOLphIn”, or “$\mathcal{DOLPHIN}$”, for example, people can access the different kinds of knowledge they possess about dolphins, such as whether they are alive, their size, and their habitats—leading us to ask whether all knowledge is accessible at the same time upon word perception, or whether some kinds of knowledge become available prior to others? The current study examines the timing of semantic access during single word reading utilizing the high temporal resolution of the ERP technique.

Studies of the time course of visual object recognition (e.g., Clarke et al., 2011, 2012; Johnson and Olshausen, 2003; Liu et al., 2009; Schendan and Kutas, 2002; Thorpe et al., 1996; VanRullen and Thorpe, 2001) have advanced our understanding of the mechanisms of human and computer vision (Serre et al., 2007b; VanRullen and Thorpe, 2002). Several researchers also have examined the time course of visual word recognition, focusing primarily on the time course of orthographic, phonological, and lexical access (Barber and Kutas, 2007; Dehaene, 1995; Grainger and Holcomb, 2009; Hauk et al., 2006a, 2009; Pylkkanen and Marantz, 2003; Sereno and Rayner, 2003). Considerably less is known about the timing of access to conceptual knowledge for written words, and about how and when this process unfolds in the brain.

There are several good reasons to delineate the timing of semantic access. For one, a better understanding of the neural timing of semantic access will constrain computational models of semantic cognition and language comprehension (Laszlo and Plaut, 2012; McRae, 2004; Rogers et al., 2004). In particular, the latencies by which different kinds of information are available from written or spoken language will inform the question of whether the initial construction of word meaning involves automatic feed-forward mechanisms or top-down feedback mechanisms, as it has for theories of visual object recognition (Serre et al., 2007a; VanRullen and Thorpe, 2002). Specifying the time course of the availability of perceptual or motor-related knowledge versus that of more abstract forms of knowledge (e.g., encyclopedic information) also will inform current debates surrounding grounded or embodied cognition (Hauk and Tschentscher, 2013; Hauk et al., 2008). Specifically, timing information will be crucial to revealing the causal role of sensory, motor, and multimodal brain regions during language comprehension and in cognition more generally (Mahon and Caramazza, 2008; Pezzulo et al., 2011).

The current study focuses on the timing of access to two different kinds of knowledge that may be acquired by different kinds of experiences and represented in separate cortical systems. The relationship between sensory/motor cortex and action-related knowledge, and the relationship between supramodal/association cortex and taxonomic knowledge, have been studied in detail using fMRI, PET, and

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neuropsychological methods, but have received considerably less attention using techniques that provide real-time stimulus-evoked electrical brain activity. We asked our participants to decide whether a written word (e.g., "tiger", "hammer") refers to a living or nonliving entity; we assume that this type of decision does not necessarily involve previous sensory or motor experience with the entity. We also asked our participants to decide whether or not the same words refer to entities that are likely to be grasped with one hand; we assume that this decision is more likely to involve knowledge acquired via sensory and motor experience. More specifically, knowledge about actions afforded by objects is likely to be acquired by some combination of observation, practice/training, repetition, and implicit or explicit imitation, whereas acquiring knowledge about what an object is or is not, probably does not rely on these kinds of experiences.

Category-related object knowledge

The living/nonliving thing distinction was first investigated in the context of category-specific deficits, wherein knowledge about a specific object domain (e.g., living things, inanimate objects) is disproportionately degraded relative to other domains following brain damage due to herpes simplex encephalitis or stroke, for example (Warrington and Mccarthy, 1983; Warrington and Shallice, 1984). Subsequent brain imaging work has shown that higher-order visual cortex responds differentially to pictures or words denoting living versus nonliving things. Specifically, ventral regions of temporal occipital cortex exhibit a medial and lateral bias for nonliving and living things, respectively (Martin, 2007). Although visual experience likely shapes this category-related neural organization to some extent, it may not be necessary given that congenitally blind individuals exhibit a similar neural organization (Mahon et al., 2009); this finding suggests that regions in the temporal lobe may differentially represent living and nonliving thing concepts based on more than perceptually-grounded feature dimensions. In sum, several primary and associative cortical regions comprising but not confined to the temporal lobes are differentially active when participants decide whether a word denotes a living versus nonliving thing (Binder et al., 2009). This is consistent with the view that a widely distributed semantic memory system may be involved in access to category-related knowledge. As we review in a later section, preliminary evidence indicates particularly fast access to this kind of knowledge.

Action-related object knowledge

Action-related information (manipulability, graspability, etc.) constitutes an important subset of object knowledge in addition to sensory-related information such as color, taste, or sound. Humans routinely interact with medium-sized objects such as bananas, knives, and telephones, and do so largely with their hands. Proper interaction with these objects (e.g., grasping the handle rather than blade of a knife) depends in part on learned information such as the actions an object affords and the material from which it is made. Some scientists have argued that long-term memory evolved primarily to guide and plan actions (Gibson, 1979; Glenberg, 1997). Gibson (1979, p. 134), for instance, hypothesized that "what we perceive when we look at objects are their affordances," and that "[w]e can differentiate the dimensions of difference if required to do so in an experiment, but what the object affords us is what we normally pay attention to." If action affordance does play this central role in our conceptual representations of objects, it seems reasonable to predict that action-related knowledge can be accessed as quickly as category-related information but to our knowledge this prediction is untested.

Whereas a large literature exists on the physiological mechanisms of grasping behavior, fewer studies have examined the conceptual knowledge of actions afforded by objects. Creem and Proffitt (2001) showed that grasping common objects while attempting to recall previously learned semantic associates (e.g., pear–apple) impaired participants' ability to grasp the objects appropriately (e.g., by the handle), whereas performing a visuospatial imagery task (mentally rotating block letters) did not, despite equal task difficulty. They inferred that grasping behavior might recruit semantic resources. Myung et al. (2006) showed that action-related information may be automatically activated during language comprehension, in that words denoting manipulable objects ("typewriter") led to enhanced processing of words denoting perceptually disparate but manipulable objects ("piano"), and that eye movements were sensitive to whether distractor images depicted manipulable or visually-matched but unmanipulable objects. These findings suggest that action-related (at least manipulability) knowledge is activated during online single word reading, although they are silent as to when this information becomes available.

Using the go/nogo task and ERPs to monitor the time course of information access

The go/no-go task paired with electrophysiological recordings has been very useful for studying the timing of information access. When people execute (go) or withhold (nogo) a motor response to visual stimuli, ERPs at frontal sites exhibit a larger negativity for nogo trials versus go trials between 100 and 400 ms after stimulus onset (Gemba and Sasaki, 1989; Sasaki et al., 1993; Simson et al., 1977). The difference between the nogo and go ERPs is called the N200 or N2 effect. Thorpe et al. (1996) employed a go/nogo paradigm to examine rapid visual categorization of briefly presented scenes that either did or did not contain an animal; participants responded only when an animal was present (go response). The resulting N200 effect was evident by 150 ms, which was argued to represent an upper limit on the time by which the brain had processed sufficient visual information to determine that the scene did not contain an animal. This inference was questioned, however, as the scenes that contained animals and those that did not likely differed in low-level visual characteristics, which also have been found to influence electrophysiological activity before 150 ms (Johnson and Olshausen, 2003). In response to this concern, VanRullen and Thorpe (2001) ensured that the images from each category appeared equally often as targets and non-targets with the same images contributing to the average go and nogo ERPs. They found that the visual characteristics of the images affected ERPs by 80 ms, but also replicated the 150 ms N200 effect. This early nogo N200 effect was obtained in studies using images. The current study used words, which provide a less direct route to meaning and are less likely to engender low-level visual stimulus confounds. These differences between words and images could delay the time course of conceptual access for words relative to that for images.

The above experiments involved a single decision on each trial, but a handful of dual-task go/nogo ERP studies have employed a dual-task paradigm, in which participants make two different decisions per item: a go/nogo decision contingent upon one kind of information available from the stimulus, and a left/right hand decision on go trials contingent upon another kind of information available from the stimulus. Some dual-task studies, for example, used black and white line drawings, where the semantic decision was whether the image depicted an animal or an object (Rodriguez-Fornells et al., 2002; Schmitt et al., 2000), or whether the image depicted an object heavier or lighter than 500 g (Schmitt et al., 2001). In all cases the nogo ERP was characterized by a larger frontal negativity starting around 200 ms post-stimulus onset than the go ERP. This is somewhat later than nogo N200 effects in the visual object categorization studies, perhaps due to the use of line drawings instead of photographs, the use of longer stimulus duration latencies, differences in instructions, or some combination thereof.

Two go/nogo neurophysiological studies have employed words rather than pictures or images. Müller and Hagoort (2006) conducted a dual-task go/nogo ERP study to contrast a semantic decision (e.g., buildings vs. consumables; weapons vs. clothing) with a syntactic