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Research report

Differing contributions of inferior prefrontal and anterior temporal cortex to concrete and abstract conceptual knowledge

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ABSTRACT

Semantic cognition is underpinned by regions involved in representing conceptual knowledge and executive control areas that provide regulation of this information according to current task requirements. Using distortion-corrected fMRI, we investigated the contributions of these two systems to abstract and concrete word comprehension. We contrasted semantic decisions made either with coherent contextual support, which encouraged retrieval of a rich conceptual representation, or with irrelevant contextual information, which instead maximised demands on control processes. Inferior prefrontal cortex was activated more when decisions were made in the presence of irrelevant context, suggesting that this region is crucial for the semantic control functions required to select appropriate aspects of meaning in the face of competing information. It also exhibited greater activation for abstract words, which reflects the fact that abstract words tend to have variable, context-dependent meanings that place higher demands on control processes. In contrast, anterior temporal regions (ATL) were most active when decisions were made with the benefit of a coherent context, suggesting a representational role. There was a graded shift in concreteness effects in this region, with dorsolateral areas particularly active for abstract words and ventromedial areas preferentially activated by concrete words. This supports the idea that concrete concepts are closely associated with visual experience and abstract concepts with auditory-verbal information; and that sub-regions of the ATL display graded specialisation for these two types of knowledge. Between these two extremes, we identified significant activations for both word types in ventrolateral ATL. This area is known to be involved in representing knowledge for concrete concepts; here we established that it is also activated by abstract concepts. These results converge with data from rTMS and neuropsychological investigations in demonstrating that representational content and task demands influence recruitment of different areas in the semantic network.

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1. Introduction

Storing and processing word meanings involves a widely distributed network of brain regions. Investigating how elements of this network respond to different types of word can provide important insights into the functional organisation of the system. This study focused on differential activations during comprehension of concrete versus abstract words (e.g., *rope vs hope*). Two main classes of theory have been proposed to account for these. The first class claims that concrete and abstract words differ in terms of their *representational substrate*. It is often claimed that abstract words have weak or impoverished semantic representations (Jones, 1985; Plaut & Shallice, 1993; Wiemer-Hastings & Xu, 2005). Jones (1985), for example, found that participants judged it easier to predicate (i.e., generate factual statements for) concrete concepts than for abstract. This representational weakness for abstracts might come about because they lack information gained from sensory experience. The most well-known of these is dual-coding theory (Paivio, 1986), which states that while both concrete and abstract concepts are used and experienced verbally, only concrete words are associated with sensory-perceptual information acquired through direct experience of their referents. Paivio proposed that verbal and sensory-perceptual information were represented in separate stores and that concrete words benefited from dual-coding in both stores, while abstract words were represented only in the verbal store. Recent studies have explored other aspects of experience that might be particularly salient for abstract concepts. Abstract words are more strongly associated with emotion and valence responses (Kousta, Vigliocco, Vinson, Andrews, & Del Campo, 2011; Vigliocco et al., 2014), for example and some abstract words are closely linked to spatial and temporal relationships (Troche, Crutch, & Reilly, 2014). These two lines of research indicate that (a) abstract words tend to have less detailed semantic representations than concrete words and (b) the representations of concrete and abstract words are associated with differential involvement of perceptual-motor, verbal and affective neural systems.

An alternative perspective holds that the meanings of abstract words are heavily dependent on the linguistic context in which they are being used (in line with the idea that knowledge of abstract words is tied strongly to language use). Initial evidence for this proposal was presented by Schwanenflugel and colleagues (Schwanenflugel, Harnishfeger, & Stowe, 1988; Schwanenflugel & Shoben, 1983), who noted that when participants were presented with an abstract word, they found it hard to generate a plausible context in which it could be used. More recently, Hoffman, Lambon Ralph, and Rogers (2013) conducted a quantitative analysis of the contextual usage of a large set of words, using a measure of contextual variability called *semantic diversity*. They found that abstract words tended to appear in a broader variety of contexts than did concrete words. We have argued that the greater semantic diversity of abstract words means that they place greater demands on executive *semantic control* processes that provide top-down regulation of knowledge (Hoffman, Jefferies, & Lambon Ralph, 2010; Hoffman, Rogers, & Lambon Ralph, 2011). Semantic control processes interact with semantic representations to ensure that the information accessed at any given moment is appropriate to the current task and context (Badre & Wagner, 2002; Jefferies, 2013; Jefferies and Lambon Ralph, 2006; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Because abstract words can occur in many different contexts, with different semantic information potentially required in each, top-down control of knowledge retrieval is thought to be particularly critical for successful comprehension of these words.

In summary, there are two perspectives on the nature of differences between concrete and abstract words, one proposing differences in the types and quantity of semantic knowledge involved in each and one proposing differential involvement of semantic control processes in each as a result of contextual variability. These two perspectives have often been treated as competing hypotheses (e.g., Binder, Westbury, McKiernan, Possing, & Medler, 2005). In this study, we evaluated a different possibility: namely that both perspectives are correct but that they apply to different neural regions within the semantic network. Semantic control is most strongly associated with the left inferior frontal gyrus (IFG) (Badre & Wagner, 2007; Thompson-Schill et al., 1997). This region shows increases in activation when participants select among semantic competitors (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Thompson-Schill et al., 1997) and when semantic ambiguity must be resolved (Bedny, McGill, & Thompson-Schill, 2008; Rodd, Davis, & Johnsrude, 2005; Zempleni, Renken, Hoeks, Hoogduin, & Stowe, 2007). In addition, lesions to left prefrontal cortex are associated with deficits in semantic control (Metzler, 2001; Noonan, Jefferies, Corbett, & Lambon Ralph, 2010; Robinson, Shallice, Bozzali, & Cipolotti, 2010) and TMS to this region selectively impairs semantic task performance when control demands are high (Whitney, Kirk, O'Sullivan, Lambon Ralph, & Jefferies, 2011, Whitney, Kirk, o'Sullivan, Lambon Ralph, & Jefferies, 2012). The semantic control hypothesis predicts that this area should show increased activation for abstract relative to concrete words (referred to hereafter as an A > C effect) because their variable meanings require greater executive regulation. A > C effects have been reported in IFG (Binder, Desai, Graves, & Conant, 2009; Wang, Conder, Blitzer, & Shinkareva, 2010) but they have not been linked specifically to executive control demands. Other researchers have suggested instead that IFG is involved in representing logical propositions that are key to the meaning of abstract concepts (Shallice & Cooper, 2013) or in integrating or "unifying" semantic knowledge of a word with prior context (Hagoort, 2005). Although most research has focused on the role of left IFG in semantic control, recent studies suggest that other regions, including posterior middle temporal gyrus, are also involved in this function (Noonan et al., 2010; Whitney, Jefferies, & Kircher, 2011; Whitney, Kirk, et al., 2011).

In contrast, the anterior temporal lobes[1] (ATL) are associated with the representation of semantic knowledge. ATL

[1] ATL is a general term which is used in slightly different ways by different researchers. In this study, we use the term ATL to refer to the entire anterior third of the temporal lobe. We use the more specific term ventral ATL (vATL) to refer to the anterior third of the fusiform and inferior temporal gyri and superior ATL (sATL) to refer to the anterior third of the superior temporal gyrus and superior temporal sulcus.

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