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Tracking competition and cognitive control during language comprehension with multi-voxel pattern analysis

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ABSTRACT

To successfully comprehend a sentence that contains a homonym, readers must select the ambiguous word's context-appropriate meaning. The outcome of this process is influenced both by top-down contextual support and bottom-up, word-specific characteristics. We examined how these factors jointly affect the neural signatures of lexical ambiguity resolution. We measured the similarity between multi-voxel patterns evoked by the same homonym in two distinct linguistic contexts: once after subjects read sentences that biased interpretation toward each homonym's most frequent, dominant meaning, and again after interpretation was biased toward a weaker, subordinate meaning. We predicted that, following a subordinate-biasing context, the dominant yet inappropriate meaning would nevertheless compete for activation, manifesting in increased similarity between the neural patterns evoked by the two word meanings. In left anterior temporal lobe (ATL), degree of within-word pattern similarity was positively predicted by the association strength of each homonym's dominant meaning. Further, within-word pattern similarity in left ATL was negatively predicted by item-specific responses in a region of left ventrolateral prefrontal cortex (VLPFC) sensitive to semantic conflict. These findings have implications for psycholinguistic models of lexical ambiguity resolution, and for the role of left VLPFC function during this process. Moreover, these findings demonstrate the utility of item-level, similarity-based analyses of fMRI data for our understanding of competition between co-activated word meanings during language comprehension.

1. Introduction

The field of psycholinguistics explains the resolution of lexical ambiguity as the consequence of selection between co-activated and competing interpretations of an ambiguous word. This view is akin to how researchers in the fields of perception, attention, and memory conceive of selection; namely, that it is a consequence of both bottom-up and top-down signals that drive competitive interactions between incompatible representations. In the present study, we take advantage of newly developed fMRI analysis techniques that have been usefully deployed to study the factors that influence selection and conflict resolution in domains of attention (e.g., Kamitani & Tong, 2005; Reddy, Kanwisher, & VanRullen, 2009) and memory (e.g., Kuhl, Rissman, Chun, & Wagner, 2011), and apply them for the first time to track competitive interactions during language comprehension. For instance, when readers must select a weaker, subordinate meaning of an ambiguous word (e.g., a river "bank") over a stronger, dominant interpretation (e.g., a money "bank"), how (and where) does the resolution of this competition manifest in neural signals?

One useful approach for identifying interference from a task-irrelevant, competing response is to look for lingering "traces" of it in spatially distributed neural response patterns using multi-voxel pattern analyses (MVPA) of fMRI data. To accomplish this, researchers first measure the multi-voxel pattern (MVP) of activity evoked by a stimulus item, and then render this item irrelevant through a task manipulation. They then measure the MVPs elicited by another stimulus item that is somehow associated with the now-irrelevant stimulus, and determine the extent to which the MVPs evoked during the updated item resemble the responses that were evoked during the now-irrelevant, original item. In the episodic memory domain, researchers have used this technique to quantify competition during targeted memory retrieval, where the same cue simultaneously elicits two associated memories, although one of the associates is task-irrelevant (e.g., Kuhl, Bainbridge, & Chun, 2012; Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015). Similarly, in a study of event comprehension, Hindy, Solomon,

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Altmann, and Thompson-Schill (2015) examined whether MVPs reflected the co-activation of two mutually exclusive states of the same object.

These studies have revealed that the degree of interference from the inappropriate representations, as manifested by their presence in MVPs in posterior cortical regions, was inversely predicted by increased recruitment of prefrontal cortex (PFC). We propose that PFC serves a domain-general role in biasing selection of task-relevant representations over competing alternatives. In the present study, we extend this proposal to the domain of lexical ambiguity resolution, and predict that PFC will similarly support the selection of MVPs evoked by subordinate, context-appropriate homonym meanings over dominant, context-inappropriate meanings.

1.1. Role of left ventrolateral prefrontal cortex in lexical ambiguity resolution

When comprehending everyday text and speech, the vast majority of words that we encounter have some degree of fluidity in their meaning, such that a single word might refer to one of several different meanings each time it is invoked. The sentence context in which a word is embedded serves as a critical cue to the word's intended meaning. Although context serves an irrefutable role in resolving this ambiguity, the relative scope and timing of its influence is largely unresolved. How (and when) do contextual factors influence word comprehension? In order to gain traction on these questions, numerous psycholinguistic experiments have investigated the online comprehension of lexically ambiguous words, such as homographic homophones. For these words (hereafter called homonyms), the same phonemic and orthographic markers refer to two or more distinct and unrelated meanings.

Because several meanings are associated with a single word form, even context-inappropriate, alternative meanings can be inadvertently activated upon encountering a homonym. Readers and listeners must rapidly select the appropriate referent at the expense of all other possible meanings, which may require resolving competition between co-activated referents. One candidate brain region for enabling a top-down bias toward context-appropriate representations is the left VLPFC (ventrolateral prefrontal cortex). In previous fMRI investigations, left VLPFC is consistently recruited during the presentation of sentences that contain homonym words, relative to unambiguous single-sense words (e.g., Hoenig & Scheef, 2009; Rodd, 2005; Rodd et al., 2012; Vitello, Warren, Devlin, & Rodd, 2014). In addition, VLPFC activity (in particular, the left-lateralized inferior frontal gyrus and inferior frontal sulcus) increases when sentences bias interpretation toward (i.e., invoke) a homonym's subordinate meaning, relative to its dominant meaning (Zempleni, Renken, Hoeks, Hoogduin, & Stowe, 2007). Left VLPFC response is greatest for subordinate-biased "polarized" homonyms, whose subordinate meanings exhibit the weakest associations to the word form (Mason & Just, 2007). This response profile is consistent with the role of a modulatory mechanism that biases the interpretation of ambiguous words, either by boosting selection of the context-appropriate meaning, dampening selection of the inappropriate meaning, or some combination of the two.

1.2. Role of left ventrolateral prefrontal cortex in domain-general conflict resolution

More generally, beyond the domain of lexical ambiguity, this same region is consistently recruited during the resolution of competition amongst conflicting, co-activated representations (e.g., Hindy, Altmann, Kalenik, & Thompson-Schill, 2012; January, Trueswell, & Thompson-Schill, 2009; Thompson-Schill, Bedny, & Goldberg, 2005). In fact, the act of selecting a weaker word meaning amidst interference from a competing, stronger meaning has much in common with the processes involved in the Stroop task (MacLeod, 1991; Stroop, 1935). During incongruent trials of Stroop color-word interference task, subjects must respond according to one stimulus dimension (i.e., the word's display color) and ignore a stronger yet task-irrelevant dimension of that same stimulus that would yield an incorrect response (i.e., the color referred to by the stimulus word).Whether selecting a weak, subordinate meaning of a homonym word during lexical ambiguity resolution or reporting a stimulus words' display color instead of its name, in both cases, subjects must select between two simultaneous and mutually exclusive representations. To examine the functional and anatomical correspondences between lexical ambiguity resolution and domain-general cognitive control processes, we functionally localized subject-specific, conflict-sensitive regions of left VLPFC using a Stroop interference paradigm.

1.3. The current study

An extensive body of psycholinguistic research indicates that the competition between potential homonym meanings is greatest when the supporting context biases readers toward the selection of a subordinate referent that is only weakly associated with the word form (e.g., river-bank) (Duffy, Morris, & Rayner, 1988; Swaab, Brown, & Hagoort, 2003; Swinney, 1979). In order to resolve this conflict between co-activated alternatives, the reader must select the subordinate yet context-appropriate meaning over the dominant yet context-inappropriate meaning. What are the neural systems that support this process? Further, what neural and psychological factors influence the degree to which a dominant, inappropriate meaning is activated? To address these questions, we tracked the competition between homonym meanings as it unfolds in the brain.

We reason that dominant and subordinate meanings should evoke distinct neural responses in regions of the brain that are sensitive to variations in lexical-semantic information. To index competition between the two meanings, we computed the similarity between their corresponding neural patterns of activation. In particular, we measured the MVPs elicited while subjects first thought about a homonym's dominant meaning, and later on, its subordinate meaning. We then examined how the degree of competition between these neural responses (i.e., their neural similarity) varied across changes in meaning frequency; sentence context; and fluctuations in left VLPFC BOLD response.

We predicted that meaning frequency would positively predict the degree of competition. That is, the association strength between a homonym word form and its dominant meaning (i.e., its meaning frequency) should predict the similarity between the dominant-biased and subordinate-biased neural patterns, such that polarized homonyms should exhibit greater within-word neural similarity than more balanced homonyms, where the meaning frequencies of the dominant and subordinate meaning are relatively more equal. Secondly, we predicted that activity in left VLPFC would be associated with the top-down selection of the context-appropriate, subordinate meaning over the inappropriate, dominant meaning, and that this would manifest as decreased competition (i.e., less within-word neural similarity) during increases in left VLPFC response. As a secondary aim, we also investigated magnitude of BOLD response during sentence comprehension, and in particular, whether left VLPFC activity is modulated by the relative location of disambiguating sentence context.