Effects of Distance between Meanings on the Neural Correlates of Semantic Ambiguity

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INTRODUCTION

Psycholinguistic studies have shown that recognition of ambiguous words is affected by the distance between meanings.

• Ambiguity at small semantic distances speeds word recognition whereas ambiguity at large distances slows word recognition (Mirman et al., 2010; Rodd et al., 2002).
• Meanings that are closer in semantic space exhibit greater competition which in turn slows word recognition.

MEG research also finds evidence for a processing cost due to competition between ambiguous word meanings that are closer in semantic space (Beretta et al., 2005; Pykkekanen et al., 2006).

fMRI research has identified several regions in which activation is modulated by processing word meanings in context:

• Bilateral inferior frontal gyrius (IFG; Blenke et al., 2009; Grindrod et al., 2008; Mason & Just, 2007; Rodd et al., 2006).
• Left inferior temporal gyrus (ITG, Rodd et al., 2006).
• Bilateral middle temporal gyrus (MTG; Zempleni et al., 2007).
• Right superior temporal gyrus (STG; Copland et al., 2007).
• Bilateral middle and superior frontal gyr (MFG, SFG; Mason & Just, 2007).

The only two published fMRI studies to investigate the neural correlates of ambiguity processing independent of context have produced inconsistent findings.

• Ambiguous words show increased activation in bilateral SFG and MFG whereas unambiguous words show increased activation in bilateral IFG, left insula, MTG and ITG (Chan et al., 2004).
• Ambiguous words show decreased activation in left IFG whereas unambiguous words show no increased activation (Hargreaves et al., 2011).

While there is a processing cost due to competition among meanings close in semantic space, how this is reflected in the neural systems underlying ambiguity processing remains unanswered. The goal of the current study is therefore to investigate whether the neural correlates of ambiguity are modulated by semantic distance.

HYPOTHESES

• Semantic distance can be viewed as a function of grammatical class, such that the meanings of same-class homonyms are closer than the meanings of different-class homonyms.
• Homonyms with two noun meanings should exhibit increased activation in the left IFG, STG and MTG relative to homonyms with a noun and verb meaning, and unambiguous words.

• Semantic distance can also be viewed as a function of meaning frequency, such that the meanings of balanced homonyms are closer than the meanings of unbalanced homonyms.
• Balanced homonyms should exhibit increased neural activation in the left IFG, STG and MTG relative to unbalanced homonyms, and unambiguous words.

METHODS

Participants: 13 right-handed, native speakers of English (7 females; Age = 24 ± 5 years; Education = 17 ± 3 years).

Materials: 30 balanced NN homonyms (match-fine, match-game), 30 unbalanced NN homonyms (brat-bread, roast-speech), 30 balanced NV homonyms (rock-stone, rock-sway), 30 unbalanced NV homonyms (duck-duck, duck-avoid), 30 unambiguous words (lake) and 150 nonwords.

Procedure: Participants viewed visually presented stimuli via a mirror mounted on the head coil and made a lexical decision via a yes/no button press.

fMRI Data Acquisition: A 3T Siemens TIM Trio MRI scanner acquired 253 functional volumes with BOLD contrast using an echo-planar imaging sequence (32 slices, TR = 2000 ms, TE = 30 ms, flip angle = 90°, matrix size = 64 × 64, FOV = 220 mm, voxel size = 3.44 × 3.44 × 3.44 mm3).

fMRI Data Preprocessing: Images were spatially registered, motion-corrected and smoothed with a Gaussian 8-mm FWHM filter using SPM8. Spatial normalization of the anatomical image to the MNI 152-subject template brain took place through ‘unified normalization’ in SPM8 (Cristin et al., 2007). Functional volumes were normalized using transformation parameters obtained from normalization of the co-registered T1 scans and resampled to 3 × 3 × 3 mm. In the first level analysis, a high-pass filter of 128 seconds was used to eliminate scanner drift. The 6 motion regressors were added to each run, as well as one regressor based on the subject’s task-specific reaction times (RTs).

fMRI Whole-Brain Analysis: For each participant, the contrast images for the main effects of the 6 different conditions were analyzed in a within-subject ANOVA with one factor of Condition. All second-level statistics were evaluated at a voxelwise significance threshold of p < .001, with a minimum cluster extent threshold (k) of 10 contiguous voxels (270 mm3).

fMRI Region of Interest (ROI) Analysis: ROI analyses were conducted with the MarsBaR toolbox in SPM (Brett et al., 2002). Percent signal change values for each of the 5 word conditions were entered into separate one-way repeated-measures ANOVAs for each cluster with Condition as the within-subjects factor. If a significant main effect was found, Bonferroni-adjusted pairwise comparisons were conducted to test for differences among condition means.

RESULTS: MRI DATA

Balanced > Unbalanced Homonyms

<table>
<thead>
<tr>
<th>ROI</th>
<th>Condition</th>
<th>Peak Cluster</th>
<th>Cluster Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>L MTG/STG [-54, -4, -11]</td>
<td>Balanced &gt; Unbalanced</td>
<td>3629 voxels</td>
<td></td>
</tr>
<tr>
<td>L MTG [-39, -61, 13]</td>
<td>Balanced &gt; Unbalanced</td>
<td>4515 voxels</td>
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Noun-Verb > Noun-Noun Homonyms

<table>
<thead>
<tr>
<th>ROI</th>
<th>Condition</th>
<th>Peak Cluster</th>
<th>Cluster Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>L IFG [-39, 53, -14]</td>
<td>Noun-Verb &gt; Noun-Noun</td>
<td>3770 voxels</td>
<td></td>
</tr>
<tr>
<td>R IFG [54, 29, 4]</td>
<td>Noun-Verb &gt; Noun-Noun</td>
<td>3902 voxels</td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY OF FINDINGS

Balanced > Unbalanced Homonyms

• Bilateral MTG extending into STG
• Left SFG
• Left middle cingulate gyrus
• Right ACC

Noun-Verb > Noun-Noun Homonyms

• Bilateral IFG extending orbitally into left MFG
• Right ACC

RESULTS: BEHAVIORAL DATA

Reaction Time

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean Reaction Time (ms)</th>
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<tbody>
<tr>
<td>Balanced</td>
<td>500 ± 50</td>
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<td>Unbalanced</td>
<td>550 ± 60</td>
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Accuracy

<table>
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<th>Condition</th>
<th>Mean Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balanced</td>
<td>90 ± 5</td>
</tr>
<tr>
<td>Unbalanced</td>
<td>85 ± 7</td>
</tr>
</tbody>
</table>

HYPOTHESES

• For balanced homonyms, increased activation in bilateral MTG/STG, left SFG, and right ACC suggests that the two equally frequent meanings are simultaneously co-activated and compete to a greater extent than the meanings of unbalanced homonyms.
• Previous studies of lexical and syntactic ambiguity resolution have shown that activation of temporal regions, especially the MTG, is modulated by the extent to which alternate interpretations compete (Mason et al., 2003; Rodd et al., 2010).
• For noun-verb homonyms, increased activation in bilateral IFG, right hippocampus extending into the STG and MTG, and right ACC argues that processing homonyms with meanings from different grammatical classes requires additional resources because of increased competition between meanings that are close in semantic space.
• The left IFG is known to be recruited under conditions of increased competition (Thompson-Szilch et al., 1997). Importantly, the lexical decision task did not explicitly require subjects to select a particular meaning of a homonym, thus increased processing demands recruit bilateral prefrontal regions under conditions of competition, even in the absence of overt selection demands imposed by the task.
• The left IFG may also have been recruited as a result of retrieving semantic information and distinct syntactic information associated with noun and verb meanings. Increased activation in the left IFG has been found for naming of transitive verbs, as compared to intransitive verbs, presumably because the former have a more complex argument structure (den Ouden et al., 2009).
• Right hemisphere activation, in areas homologous to classic left hemisphere language areas, was also observed. Activation of right frontal and temporal areas has been found in previous neuroimaging studies of semantic ambiguity (Chan et al., 2004; Zempleni et al., 2007).

CONCLUSIONS

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