NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 36 (2007) 924 – 932

# Time course of semantic processes during sentence comprehension: An fMRI study

Colin Humphries,* Jeffrey R. Binder, David A. Medler, and Einat Liebenthal

*Department of Neurology, MEB 4550, 8701 Watertown Plank Rd, Medical College of Wisconsin, Milwaukee, WI 53226, USA*

Received 9 December 2006; revised 7 March 2007; accepted 16 March 2007
Available online 10 April 2007

**The ability to create new meanings from combinations of words is one important function of the language system. We investigated the neural correlates of combinatorial semantic processing using fMRI. During scanning, participants performed a rating task on auditory word or pseudoword strings that differed in the presence of combinatorial and word-level semantic information. Stimuli included normal sentences comprised of thematically related words that could be readily combined to produce a more complex meaning, semantically incongruent sentences in which content words were randomly replaced with other content words, pseudoword sentences, and versions of these three sentence types in which syntactic structure was removed by randomly re-ordering the words. Several regions showed greater BOLD signal for stimuli with words than for those with pseudowords, including the left angular gyrus, left superior temporal sulcus, and left inferior frontal gyrus, suggesting that these areas are involved in semantic access at the single word level. In the angular and inferior frontal gyri these differences emerged early in the course of the hemodynamic response. An effect of combinatorial semantic structure was observed in the left angular gyrus and left lateral temporal lobe, which showed greater activation for normal compared to semantically incongruent sentences. These effects appeared later in the time course of the hemodynamic response, beginning after the entire stimulus had been presented. The data indicate a complex spatiotemporal pattern of activity associated with computation of word and sentence-level semantic information, and suggest a particular role for the left angular gyrus in processing overall sentence meaning.**


## Introduction

In comprehending a sentence, spoken or written sensory stimuli must be mapped onto meanings. This is a dynamic process involving determining not only the meanings of individual words but also the meanings of combinations of words that are usually embedded within a syntactic framework. Many studies investigating the neural organization of semantic processing have focused on the processing of single words and have implicated a distributed network of brain areas in this function (for reviews see Martin and Chao, 2001; Thompson-Schill, 2003; Damasio et al., 2004). Less is known about how the semantic system deals with groups of words. For example, the nouns *shipwreck* and *basketball* each have their own individual meanings, but when they are combined, as in the sentence *The shipwreck victim survived by clinging to a basketball*, a new and much more complex semantic representation is created, in which the whole is greater than the simple sum of the parts and includes the now salient concept that *basketballs float*.[1] We refer to this process of combining the meanings of multiple words as "combinatorial semantic processing".

Prior research on the neural correlates of combinatorial semantic processing has mainly focused on how single words are integrated within a sentence. An event related potential (ERP) component called the N400 varies with several lexical–semantic factors influencing sentence processing (Kutas and Hillyard, 1980; Kutas and Federmeier, 2000). For example, the N400 is larger when a word in the sentence is semantically unexpected but grammatically correct, as in the final word of the sentence, *The man ate a window*, compared to when a word is congruent with the semantic context (e.g., *The man ate a sandwich*). Similar semantically anomalous sentences have been used in fMRI experiments, which have shown greater activation for sentences with semantic anomalies in a variety of regions in the left inferior frontal, left inferior parietal, and left posterior temporal lobes (Friederici et al., 2003; Newman et al., 2003; Luke et al., 2002; Kuperberg et al., 2000; Ni et al., 2000; Kang et al., 1999). The prevailing interpretation of such results is that the anomalous word is more difficult to integrate into the established semantic context, thus the increase in activation is attributed to increased neural activity devoted to combinatorial semantic processing (Kutas and Federmeier, 2000).

* Corresponding author. Fax: +1 414 456 6562.
*E-mail address:* chumphri@mcw.edu (C. Humphries).
**Available online on ScienceDirect (www.sciencedirect.com).**

[1] This example of combinatorial semantic processing was adapted from Barsalou, L.W. (1982) "Context-independent and context-dependent information in concepts", Memory and Cognition, 10, 82–93.

1053-8119/$ - see front matter 
doi:10.1016/j.neuroimage.2007.03.059

A different approach to studying combinatorial semantic processing is to compare processing of normal sentences with processing of grammatically correct sentences in which the content words (i.e., nouns, verbs, adjectives) have been selected at random and are therefore thematically unrelated (Humphries et al., 2006; Mazoyer et al., 1993; Vandenberghe et al., 2002). Because the words are no longer thematically related, the subject is unable to build a coherent semantic representation larger than that given by each individual word. Results of this experiment have varied, with one study finding greater activation in the anterior temporal pole for the semantically random stimuli over the normal stimuli (Vandenberghe et al., 2002), and other studies showing greater activation for the semantically normal over the semantically random stimuli in left middle temporal areas (Humphries et al., 2006; Mazoyer et al., 1993) and left inferior parietal lobe (Humphries et al., 2006). Some of these differences could be due to differences in the tasks that were performed by the participants, which made different demands on overt semantic interpretation (Humphries et al., 2006).

One difficulty in studying combinatorial semantic processing with functional imaging is that there are likely to be several component processes involved, each occurring on different time scales. For example, during comprehension of a sentence, access to the meanings of individual words starts as soon as the sentence begins. Building and representing an overall meaning, on the other hand, probably starts later in the sentence and may even continue after the stimulus has ended. In event-related fMRI studies, these different processes might be reflected by differences in the BOLD time course. The most common approach used in analyzing such studies is to average the activation across the entire stimulus trial. However, if the effect of interest changes over time (i.e., there is an interaction between time from stimulus onset and type of process activated), then averaging the response over time will not provide a complete and accurate picture of these component processes.

We examined these issues by acquiring fMRI data while subjects were presented with sentences and word lists with varying degrees of combinatorial and word-level semantic information. These materials included semantically congruent sentences and word lists, in which all of the content words (nouns, verbs, adjectives) were thematically related to a concrete event; semantically random sentences and word lists, in which the content words were thematically unrelated; and pseudoword sentences and word lists, in which the content words were replaced by meaningless pseudowords. Results from this study were published previously using contrasts that summed over a range of time points, showing large regions of temporal and parietal cortex to be involved in combinatorial semantic processing (Humphries et al., 2006). In the current study, we reanalyzed the data using a more sensitive, time-based analysis to better examine the time course of activation in these semantic processing areas. We hypothesized that combinatorial and word-level semantic processing would be active at different times during comprehension of the stimulus, with word-level processing occurring relatively early and combinatorial occurring relatively late. Analyzing individual time points should increase sensitivity to these semantic effects by avoiding averaging over a large number of possibly inactive time points. In addition, this approach will allow us to characterize differences in onset times of combinatorial and word-level related activity based on contrasts between conditions. Knowledge of the timing of these processes will allow us to better define the function of identified semantic regions, especially those regions that show activation both during word-level and during combinatorial processing.

## Methods

### Subjects

FMRI data were collected from 21 right-handed, native English-speaking subjects (7 male, 14 female; ages 23–48) with normal hearing. Subjects gave informed consent under a protocol approved by the IRB committee of the Medical College of Wisconsin and were compensated for their participation.

### Materials

The stimuli were trains of spoken words and word-like pseudowords. The experiment consisted of six conditions generated in the following ways. *Semantically congruent sentences* were novel sentences describing concrete events in active voice and simple past tense (e.g., "the man on vacation lost a bag and a wallet"). The number of words in each sentence varied between 9 and 13 (mean = 10.8). *Semantically random sentences* were created by replacing the content words in the semantically congruent sentences with randomly selected content words of the same word class (i.e., noun, adjective, verb) (e.g., "the freeway on a pie watched a house and a window"). *Pseudoword sentences* were generated by replacing all of the content words in the semantically congruent sentences with pseudowords (e.g., "the solims on a sonting grilloted a yome and a sovir"). The pseudowords were generated by a Markov chaining process using bi-gram frequencies from the CELEX database and contained the same number of syllables as the matched content word (Medler and Binder, 2005). Pseudowords representing verbs had an additional '-ed' suffix added to the end of the word. Three sets of word list stimuli were also created from the three sentence conditions by replacing the function words in the sentences with randomly selected function words and then randomizing the order of the words in the list, producing *semantically congruent word lists* (e.g., "on vacation lost then a and bag wallet man then a"), *semantically random word lists* (e.g., "a ball the a the spilled librarian in sign through fire"), and *pseudoword word lists* (e.g., "rooned the sif into lilf the and the foig aurene to").

There were 40 stimuli per condition. To remove any phrase-level prosodic contours that might distinguish the sentences from the word lists, the words and pseudoword used in the experiment were recorded individually in a random order, and the source talker (JRB) used the same neutral tone with slightly falling intonation contour for each item. To create the sentences and word lists, the individual word recordings were normalized by total energy and concatenated using Matlab (Mathworks Inc, Nattick, MA). Spacing was added between each word in the sentence or word list so that the total length of each stimulus was 6.1 s.

### Procedure

Prior to scanning, subjects were instructed on the rating task to be performed in the scanner using several examples of each of the six conditions. During the experiment, subjects rated each stimulus on how meaningful it was using a scale between 1 and 4 (4 = most meaningful) by pressing one of four keys on an MRI compatible keypad. They were told to listen to the entire stimulus before making a response.

FMRI data were collected on a 1.5 Tesla GE scanner. For each subject a high-resolution T1-weighted anatomical scan was collected