

AN MEG STUDY OF LEXICAL DECISION*

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1 Overview

This paper is one subpart of a larger body of research devoted to exploring the neural basis of linguistic knowledge. Since so little is still known about how language is encoded in the neurons of the brain, the approach we have adopted is to look for neural responses that correlate with well-known effects in language processing and production.

We used MEG to study neural responses during a lexical decision task. The lexical decision task has been used in the behavioural literature to test models of lexical access, using only reaction times and error rates as a measure of what is going on in the brain (Rubenstein et al. 1970, Forster & Chambers 1973, Frederiksen & Kroll 1976, Balota & Chumbley 1984, Kroll & Merves 1986). For our experiment, the stimuli varied along several dimensions known to affect reaction time. The goal was to find a neural response whose time course correlates with the observed pattern of button-press reaction times.

We succeeded in finding a response whose latency tracks reaction time measurements along several dimensions. The response is in temporal cortex, occurring on average about 240ms after presentation of the stimulus. Previous research has shown that temporal cortex is one locus of linguistic activity—for example, temporal lobe damage can give rise to Wernicke's aphasia (but see Bogen & Bogen 1976 for discussion of the diversity of lesion sites for Wernicke's aphasics). We also found an earlier response at around 160ms, whose timing is insensitive to the properties of the stimuli that cause reaction-time differences. This response seems to arise in occipito-parietal cortex, an area to which higher-order visual, auditory and somatic areas project, and which is thought to synthesize information from different modalities before further perceptual and linguistic processing.

These results mean that we have identified a plausible candidate for a response in the central nervous system that reflects lexical access. The 240ms response can now be used to investigate how lexical knowledge is encoded in the brain, so as to provide new insights into the neural basis of language processing and production.

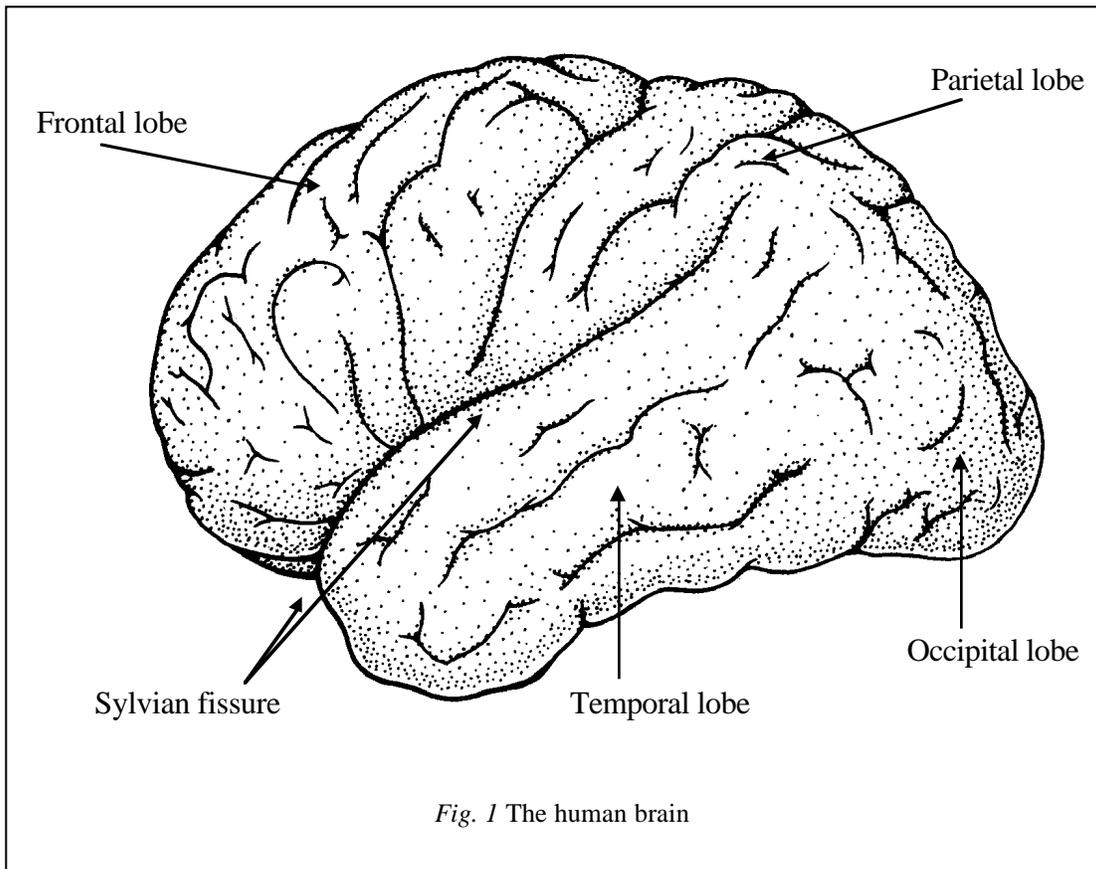
Before describing our experimental design and results, I will present an overview of some relevant anatomical details, as well as some background on MEG and lexical decision.

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2 A Quick Tour of The Brain

MEG is a technique that can be used to study the timing and localization of neural responses in the brain. Since we will refer to various anatomical structures in the brain, it will be of use to review these briefly.

We will be concerned with the cerebral cortex, which forms the surface of the cerebral hemispheres. The cortex is folded into numerous convolutions, consisting of gyri (convexities) and sulci (concavities). It is divided into four lobes, the frontal, temporal, parietal and occipital, as shown in Fig. 1. The temporal lobe borders on the frontal and parietal lobes, divided from them by the Sylvian fissure. Its uppermost surface is known as the superior temporal plane. For our experiment, we positioned the sensors over auditory cortex and over occipito-parietal cortex.



3 Magnetoencephalography

MEG is short for magnetoencephalography. This is a brain recording technique that uses tiny magnetic fields recorded at the scalp to estimate the location of neural activity in the brain. Our system uses 37 sensors arranged in a circular array approximately the size of a saucer. The sensors are at the bottom of a large cryogenic dewar. The dewar is placed close to the head, where each sensor records the local magnetic field strength from one millisecond to the next. Recordings took place in a magnetically shielded room, with subjects lying down on one side.

The magnetic fields measured by MEG are generated by electrical potentials that arise when groups of neurons in the cortex fire together. Recall that magnetic fields travel in a circle around the flow of an electrical current. By measuring these fields, we can infer the source of the current. This only works if the current flows at a tangent to the curvature of the skull; if it flows radially outward from the head, the magnetic fields cancel one another out. This means that activity in certain areas cannot be measured using MEG.

The main source of the activity measured by MEG is in the pyramidal cells of the cortex. These cells are lined up to fire at an angle perpendicular to the convoluted surface of the cortex. Pyramidal cells in a sulcus will fire at an angle to the curvature of the head, while cells on a gyrus will fire radially outward, such that the magnetic fields at the scalp will cancel each other out. As a result, MEG is best suited to measuring activity on either side of a sulcus. Fortunately, there is substantial evidence that linguistically related brain activity occurs in the area around the Sylvian fissure, a large sulcus that divides the temporal lobe from the parietal and frontal lobes. For example, both Broca's and Wernicke's areas are traditionally located along this fissure.¹

Another technique for studying electromagnetic brain activity is ERP, which measures the electrical potentials generated by neurons firing. Unlike magnetic fields, electrical potentials are warped by travelling through brain tissue and bone, which complicates the process of localizing the source. Currently, very little work in neuropsychology uses ERP source localizations. On the other hand, it is possible to measure potentials generated by a current flowing radially outward from the head, so ERP could be used to measure activity from areas inaccessible to MEG.

Based on recordings from the MEG sensors, we can calculate the best single dipolar current source for the measured magnetic fields at each sampling interval. This gives us an idea of the strength and coordinates of local neural activity, millisecond by millisecond. Then we can map the source onto an MRI scan of the individual subject's brain, to get an idea of the anatomical localization.

Other methods for studying brain activity measure patterns of blood flow and metabolism in the brain rather than electrical activity. These include positron emission tomography, or PET, and blood-oxygenation-level dependent functional magnetic resonance imaging, or BOLD fMRI. Like MEG, these methods have good spatial resolution, allowing highly accurate localizations. However, the temporal resolution is not as good as with MEG, both because the rate of collecting information is orders of magnitude slower, and because oxygenated blood distribution itself is a fairly coarse-grained indicator of neural activity. The fine-grained temporal resolution of MEG makes it possible to connect the time course of neural responses with the huge psycholinguistic literature on reaction-time effects.

4 Background: Lexical Decision

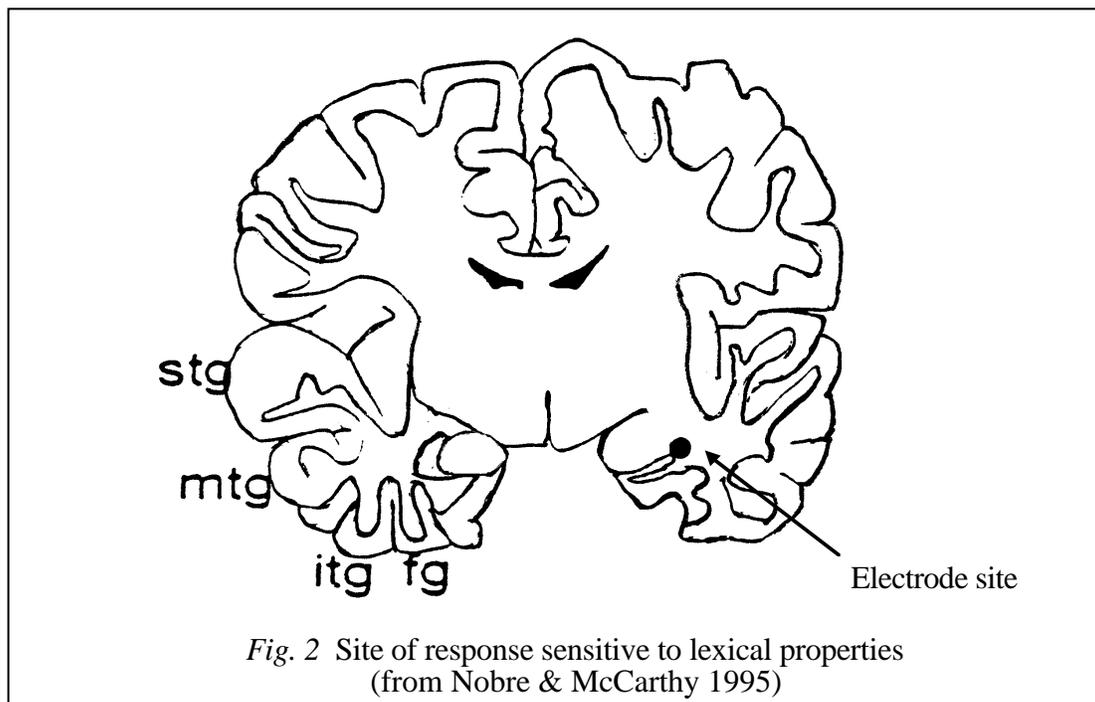
The paradigm we used from the psycholinguistic literature was the lexical decision task. In this task, the subject is presented with a series of wordlike strings, and decides for each string whether it is a word or a nonword. The strings may be presented visually or auditorily, and the decision is usually recorded by means of a button-press response. With a visual presentation, nonwords are of two main types, usually called 'pronounceable' and 'nonpronounceable.'² Pronounceable nonwords follow the orthographic conventions of the language of the experiment, in this case English, so that they would be pronounceable according to English phonotactics. Nonpronounceable nonwords violate the orthographic conventions such that pronouncing them would violate the phonotactics of the language.

¹ For more details on MEG, see Phillips et al. 1995.

² As pointed out by Denis Bouchard, the use of these terms in the context of visually presented stimuli should not be taken to suggest that the processing of auditory and visual words is identical.

Behavioural studies have shown that reaction time in the lexical decision task is affected by a number of different factors. For word stimuli, there is a substantial effect of frequency, with shorter reaction times for higher-frequency words than lower-frequency words (Rubenstein et al. 1970, Forster & Chambers 1973). The length of the string has an effect on reaction time for both words and nonwords, with a shorter RT for shorter strings. Also, reaction time is much faster for nonpronounceable nonwords than for pronounceable nonwords, which are more easily mistaken for words (Frederiksen & Kroll 1976).

In addition to the psycholinguistic results, there are also some neurolinguistic studies that make predictions about the lexical decision task. For example, Nobre & McCarthy 1995 used intracranial recordings to study the lexical decision task. This method involves measuring electrical potentials from depth electrodes in patients with exposed brains. Using electrodes embedded in the anterior medial temporal lobe, they compared responses to visually presented words and pronounceable and non-pronounceable nonwords. The view in Fig. 2 is a coronal slice through the brain, seen from the front; the large arrow points to an electrode site near the amygdala in the left anterior temporal lobe. This site and sites nearby were found to be sensitive to the word/nonword distinction and to the difference between content and function words. These results indicate a temporal response at about 400ms post-stimulus onset that is associated with lexical access.



Recent MEG studies indicate an earlier temporal response for lexical access. In a study of responses to strings of Japanese syllabic katakana and hiragana characters, Kuriki et al. 1996 reported three early response components in the left hemisphere. The first was a response in the occipital lobe between 160-190ms, and the others were in the temporal lobe—one between 230-270ms, and one between 310-375ms. The occipital response suggests visual processing, which is known to occur in occipital cortex, while the later responses in the temporal region may indicate lexical search.

A third study, Salmelin et al. 1996, used MEG to compare Finnish dyslexics and normals in a task where they had to identify the word for 'giraffe' in a series of visually presented words and pronounceable and nonpronounceable nonwords. They found a 220ms response to words in normals that localizes to the area around the left Sylvian fissure, which is also in the temporal region.

Based on these studies, we expect early activity in the occipital area that reflects visual processing, and activity in the temporal area sometime after 200ms that reflects lexical access.

5 Design and Methods

In our experiment, we had the subject carry out a lexical decision task, while we took MEG measurements from the left hemisphere. This way, we could directly correlate neural activity with button-press reaction times.

A series of 100 words and 100 nonwords were visually presented one by one in randomized order, at the center of a screen. The subject would press one of two buttons as quickly as possible to indicate whether the string was a word or a nonword. Following the button press was a random inter-stimulus interval, between 100-900 ms, during which a fixation point appeared at the centre of the screen.

We presented words and nonwords in two conditions, one with pronounceable and one with nonpronounceable nonwords. The strings varied from three to eight letters in length.³ The words were taken from lists in a behavioural study; they were abstract and concrete nouns that varied along a continuous scale of frequency from 1-447 instances per million (Kucera & Francis 1967). Pronounceable nonwords were created by changing one letter of an existing word, and nonpronounceable nonwords were chosen from randomly generated strings of letters (see Table 1).⁴

word	<i>freq</i>	pr. nonword	np. nonword
BAG	42	FUG	HFL
FATE	33	BOMY	UEKC
WHEAT	9	OPERT	PUGXG
THEORY	129	RUNGLE	YSGULV
WINDOWS	53	EVERING	NRLGCZT
ATROCITY	2	STALTION	BHYMCRNX

Table 1. Sample Stimuli

At the same time, the magnetic field on the surface of the skull was measured using MEG. Given the predictions of previous experiments, we placed the MEG sensor array over left temporal and occipito-parietal cortex. For a number of subjects, we also measured the auditory M100, which is a characteristic response in auditory cortex about 100ms after the onset of a sound. The localization of the M100 served as a functional landmark for other responses from the same subject. This information is useful even in addition to anatomical MRI localizations, since the same anatomical structures in the brain do not always subserve the same functions.

6 Results

Our subjects showed the typical behavioural effects for lexical decision. In the condition with words and pronounceable nonwords, there was a significant decrease in reaction time to words as

³ Frederiksen & Kroll 1976 shows that syllabic properties give rise to no significant RT effects independent of word length. Kroll & Merves 1986 shows that concreteness has no RT effect except when blocks of concrete words are presented before blocks of abstract words, in which case RT for abstract words increases.

⁴ It should be noted that the initial part of some nonpronounceable nonwords obeys English orthographic conventions, while others are gibberish from the first two letters. As Michel de Graff (p.c.) notes, the distinction has consequences for lexical processing, and can be studied independently.

frequency increased ($R^2=2.6\%$, $p<0.004$; Fig. 3). There was also a faster reaction time for shorter strings, including words and nonwords ($R^2=2.9\%$, $p<0.0001$).⁵ What we wanted to do was find a neural response whose timing correlates with these reaction times.

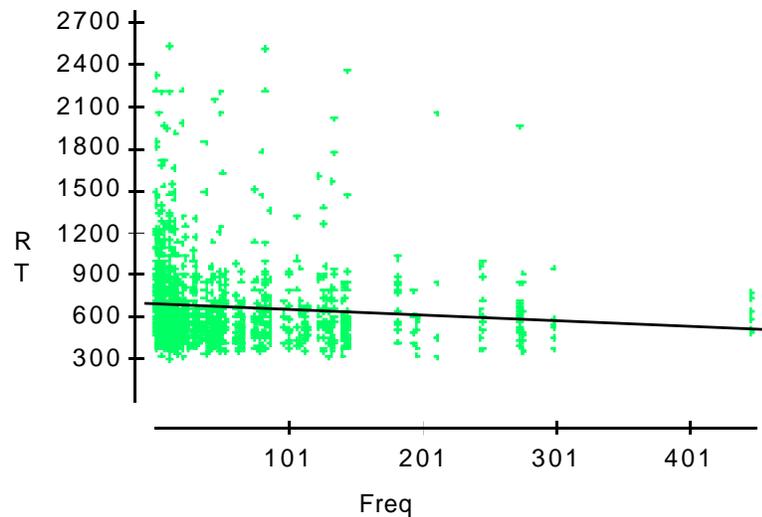


Fig. 3 Button-press reaction time as a factor of word frequency (n=4)

We identified two early peaks of cortical magnetic activity, at around 160ms and 240ms post-stimulus onset. Fig. 4 shows RMS, which is a summary of the total magnetic activity across all 37 sensors at each point in time. The X axis shows latency in milliseconds. Peaks of magnetic activity often indicate a strong dipolar current.

⁵ Word responses were also significantly faster than pronounceable nonwords and slower than nonpronounceable nonwords. However, the lexical decision task is not designed to focus on the difference between words and nonwords, since subjects may perceive one response as the 'yes' response, and the other as 'no'. In this case, word/nonword differences in both RT and MEG measurements interact with the yes/no difference. Thanks to Molly Potter for discussion of this issue.

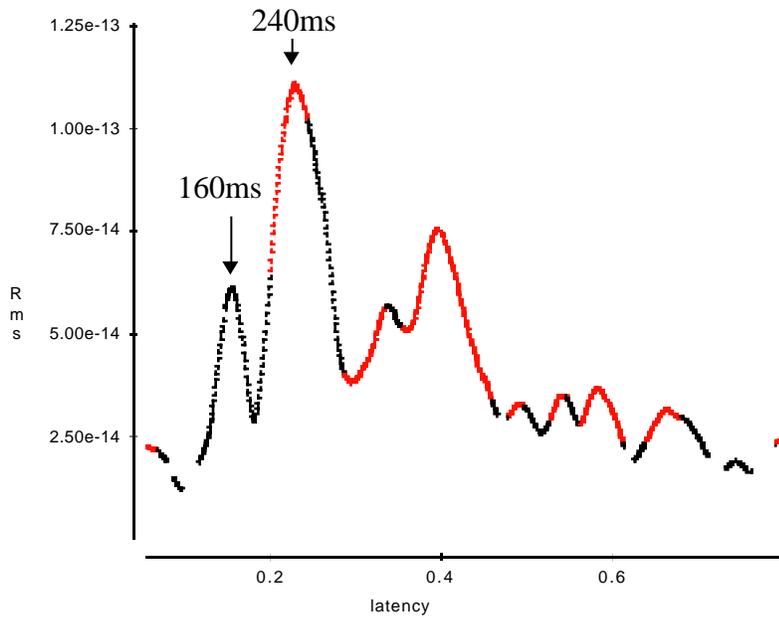


Fig. 4 RMS peaks for averaged responses to one condition for one subject

The 160ms peak showed no effects of any lexical properties, suggesting that it is unconnected with lexical access. However, the latency of the later peak varied as a factor of frequency and string length. This peak had an earlier latency for high-frequency words than for low-frequency words (see Fig. 5). In the condition with words and nonpronounceable nonwords, the later peak also has an earlier latency for shorter strings. The latency effects on the second peak match the effects on button-press reaction time, which also shows earlier responses for higher-frequency words and shorter strings. These results indicate that the later response has access to lexical properties.

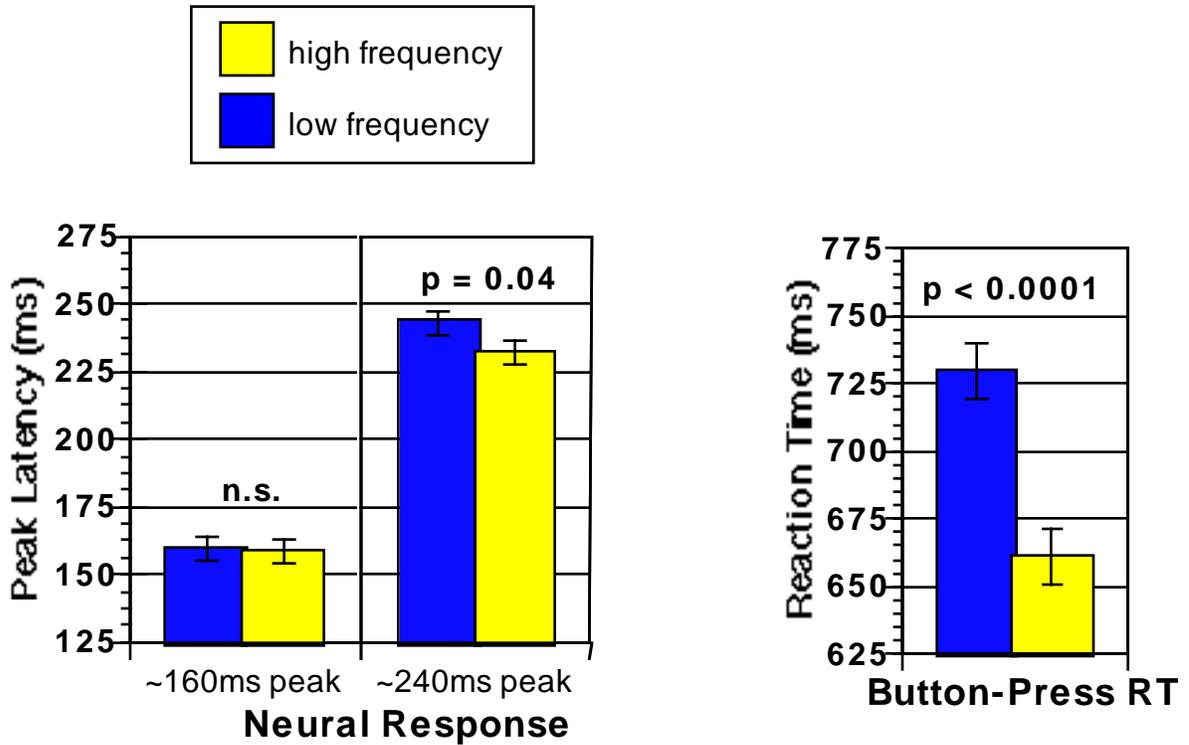


Fig. 5 Effect of word frequency on MEG and button-press reaction times

These conclusions are partially supported by localization evidence. Where it has a reliable localization, the early peak localizes to occipito-parietal cortex. Fig. 6 indicates the position of this response for one subject. This image shows a sagittal slice through the brain, several centimetres to the left of centre.

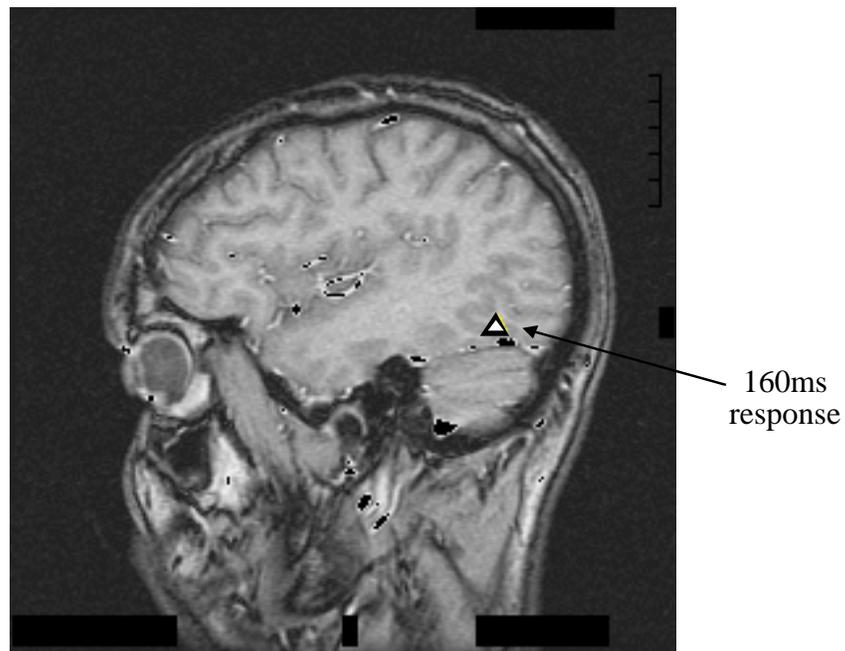


Fig. 6 Localization of ~160ms peak in occipito-parietal cortex

Fig. 7 is a 3D localization of both peaks for one subject, also showing the typical location of the auditory M100 response. For this subject, the later peak localizes to an area below and further in than the auditory response in most subjects, which suggests a region in temporal cortex below the superior temporal plane. Notice that the early peak is higher and more posterior than the later one, suggesting that the early peak is in occipito-parietal cortex, a visual processing region.

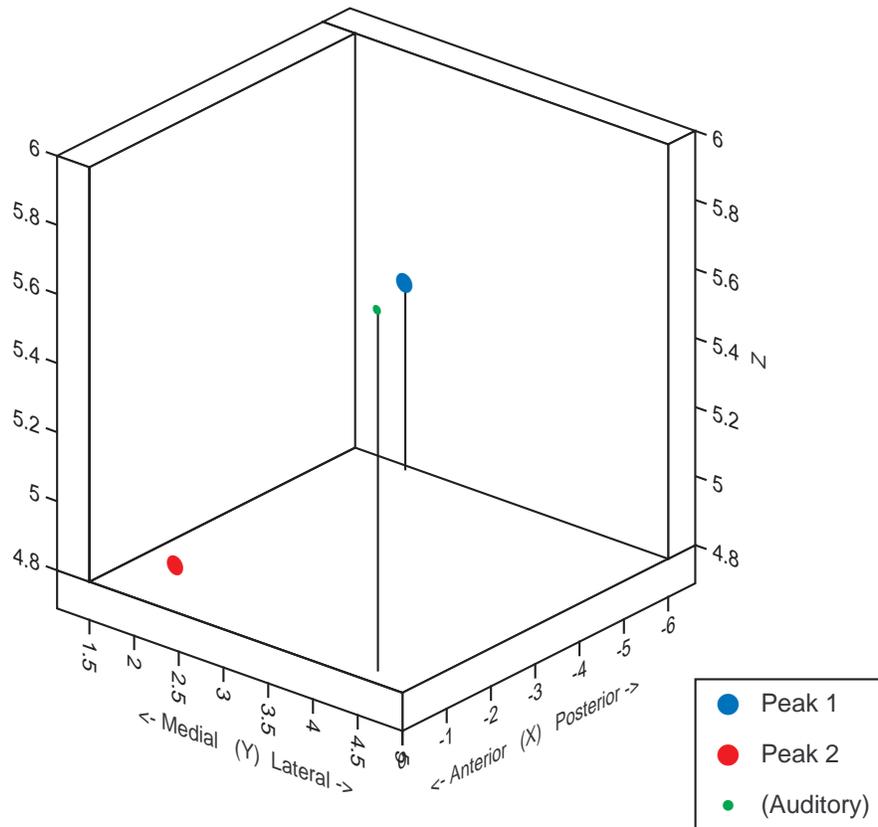


Fig. 7 Localization of response to word stimulus for one subject (word / nonpronounceable nonword condition)

7 Conclusions

These results support the view that the temporal region is implicated in lexical access at least as early as 240ms. We found no evidence for lexical access before this point in the processing sequence, but there is evidence for a visual processing response at around 160ms in occipito-parietal cortex. What we have found so far provides a basis for further investigations of language processing and production, particularly with regard to the specific mechanisms of lexical storage and access.

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