Event-related magnetic fields of the human brain during semantic information processing

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Within the past decade, substantial advances in understanding the functional organization of sensory cortex have been made through the measurement of sensory-evoked magnetic fields. The application of magnetic field recordings to "higher cognitive functions" is a more recent endeavor. We have recently described neuromagnetic sources of activity associated with selective auditory attention (Arthur et al., 1989, 1990), selective visual attention (Aine et al., 1989) and under conditions which elicit the "P300" component of the ERP (Lewine et al., 1989). In this paper, we focus on magnetic fields recorded in tasks which reflect the violation of linguistic expectancies. Kutas and Hillyard (1980) have shown that semantic anomalies elicit a large negative ERP wave which peaks around 400 ms. The purpose of this study was to determine whether a neuromagnetic analog of the N400 could be recorded and to provide preliminary information as to its neural source or sources.

Methods

Subjects. Six subjects (5 females, average age = 19.6 years; range 18-22 years) participated in the experiment. Five subjects were right-handed and 1 was left-handed as determined by self-report.

Procedure. Each subject was tested in an aluminium and mu-metal magnetically-shielded room. Neuromagnetic activity was recorded with a 7-channel SQUID-coupled second-order gradiometer system. Data were recorded from 14 (n = 3), 28 (n = 1), 35 (n = 1) or 42 (n = 1) sensor positions over the right hemisphere of each subject. Four of the subjects received additional left hemisphere mapping from 14 (n = 1), 21 (n = 1) or 28 (n = 2) sensor positions. Sensor positions were expressed in an X, Y, Z coordinate system relative to head landmarks: two periauricular points and the nasion. The line passing through the two periauricular points was the Y axis, the line bisecting the Y axis passing through the nasion was the X axis and the line perpendicular to the X-Y plane was the Z axis. The intersection of these 3 lines (X = 0, Y = 0, Z = 0) was at head center.

EEG activity was recorded simultaneously with the magnetic data between an electrode at Cz and one located on the mastoid contralateral to the MEG recording location. EOG activity was recorded simultaneously with an electrode placed next to either the left or right outer canthus referenced to the contralateral mastoid. The analog signals were bandpass filtered between 0.1 Hz and 50 Hz and digitized at a 200 Hz sampling rate. Trials characterized by artifacts exceeding 80 μV, including eye-movements, muscle activity or electromagnetic interference of the gradiometer system, were excluded from averages.

Thirty semantically congruent and thirty incongruent sentences were presented at each recording location. There were 10 different sets of 30 congruent and 30 incongruent sentences so that different sentences were presented at each recording location. Sentences were made semantically incongruent by presenting a semantically inappropriate last word. These sentences were presented one word at a time at an inter-word interval of 500 ms and the subject's task was to read each sentence silently for comprehension. All data to be reported concern the neural response to the last word of sentences only.

Results

To determine whether the conditions of this experiment elicited an N400 component, we compared the neural responses to the semantically congruent and incongruent sentences. We then examined magnetic data for differences between congruent and incongruent responses. If the magnetic difference occurred within the same latency range as the electrical N400, it was concluded that the magnetic counterpart to the N400 (M400) was recorded. N400 components were produced by all subjects. M400 responses were observed over the left hemispheres of all four subjects whose left hemispheres were examined. Figure 1 shows the N400 and left hemisphere M400 responses from anterior and posterior temporal locations for one subject. There is a consistent difference in the waveforms evoked by the incongruently ending sentences compared to the semantically congruent sentences. By contrast, the vast majority of right hemisphere recordings revealed no difference in the response to congruent and

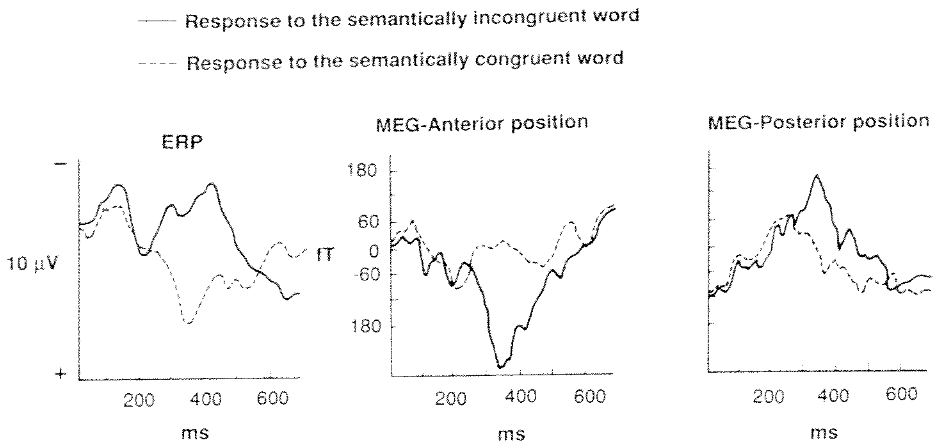

Figure 1: Sample electrical and magnetic responses to the last word in sentences are shown for subject 2 (JN). Magnetic and electric responses have similar waveshapes, although the ERP waveform has inverted in polarity across anterior and posterior temporal positions. Magnetic fields recorded from anterior temporal and temporo-parietal positions are of opposite magnitude.

incongruent sentences. Only one subject exhibited a weak M400 response over the right hemisphere. In spite of homologous left and right hemisphere recording locations in this subject, the right hemisphere difference between congruent and incongruently elicited responses was too small and unreliable to warrant further analysis.

To determine whether the source of the M400 could be adequately localized using a single equivalent current dipole (ECD) model, 28 sensor locations were mapped over the left hemisphere in two subjects. The isofield patterns for these two subjects are given in Figure 2. The isofield pattern is approximately dipolar in both subjects: there are two major extrema, a positive extremum associated with emerging field and a negative extremum of re-entering flux.

To determine the best-fitting source locations of the magnetic activity, a current dipole in a conducting sphere was used as a theoretical model. The five parameters determining the position and orientation of the dipole model were found by an iterative least-squares fit to the observed fields using a modified Levenberg-Marquardt algorithm. The head-centered X, Y, Z coordinates for the computed equivalent current dipoles are given in Table 1.

Errors in ECD location were assessed using Monte Carlo simulations based on the standard deviation of the pre-stimulus baseline (see Medvick et al., 1989 for details). Note that the X and Z locations are fairly consistent for the two subjects, while the Y locations differ by 2 cm between the two subjects. Furthermore, there is greater uncertainty in defining the exact Y-axis location (standard deviation of the mean = 0.5 cm). On the basis of projecting these ECD locations onto a magnetic resonance image (MRI) of a human adult brain (not the brain of either subject) the equivalent

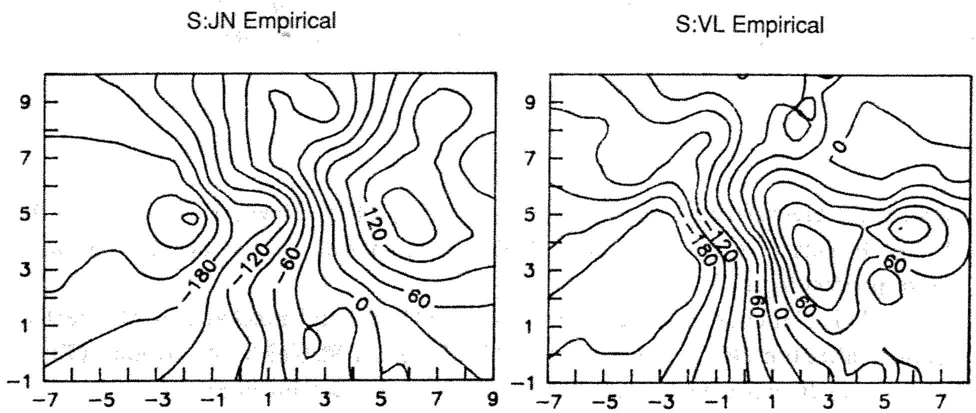

Figure 2: Isofield contour map of difference responses (congruent ending - incongruent terminal word) for subjects 1 (VL) & 2 (JN). The origin of the horizontal (X) axis is at the periauricular point and the origin of the vertical (Z) axis is at the outer canthus of the eye. Field amplitudes are indicated in femto Tesla.

Table 1: Computed locations of the best-fitting equivalent current dipoles describing the source of left hemisphere M400 components in 2 subjects. Distances are measured in centimeters from the center of the head and projecting out the positive X axis toward the nasion; the positive Y axis toward the left ear; and the Z axis toward the vertex. Standard deviation of location in each axis are based on 50-run Monte Carlo simulations for each ECD solution.

Subject	X	S.D.	Y	S.D.	Z	S.D.
1	-0.3	0.2	1.2	0.5	4.8	0.3
2	0.0	0.2	3.2	0.5	4.5	0.4

source is estimated to be at a depth of approximately 6 cm within the left posterior temporal or temporo-parietal regions.

Discussion

In all subjects tested, left hemisphere M400 components were observed. Of all subjects' right hemisphere data, only the data for one subject exhibited an M400. Because detailed mapping was not carried out over left and right hemispheres of all subjects, this varying pattern of results must be viewed with caution. Furthermore, there is no neuroanatomical measure of ECD locations, so the precise anatomical substrate of sources cannot be determined. The pattern of results is consistent with both a deep temporal (point) source or, alternatively, an extended superficial source possibly in parietal cortex. Further research aimed at defining possible hemispheric asymmetries in the generation of the M400 component is underway.

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