Response to silent Kanji reading of the native Japanese and German in task subtraction magnetoencephalography

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Accepted 31 March 1998

Abstract

The neuromagnetic activities evoked by semantic processing were localized by magnetoencephalography (MEG). We observed distinct time courses of the activities in native speaking Japanese subjects (Japanese speaker) and German subjects (German speaker) during silent reading of Japanese letters; Kanji and meaningless figures made by deforming the Arabian letters. There were significant differences in amplitude of the activities between Kanji and meaningless figure stimuli. The responses with meaningless figure stimuli were subtracted from those with Kanji stimuli to demonstrate the semantic responses. Earlier responses peaked at about 273.3 ± 50.8 and 245.0 ± 23.8 ms (mean ± S.D.) and were mainly located in the right fusiform gyrus (FuG) in the Japanese and German speakers, respectively. All the Japanese speakers constantly showed additional later responses in the left superior temporal gyrus (STG) and the supramarginal gyrus (SmG) at approximately 616.1 ± 105.5 ms, whereas no further activity was observed in the German speakers who did not know the meaning of each Kanji. Because the later responses in the STG and SmG in the Japanese speakers were only observed in their dominant hemisphere, we believe the source of these responses to be part of the neural basis of Kanji semantic processing. The task subtraction MEG analysis could be a powerful method to discriminate distinct responses and visualize the neural networks involved in semantic processing. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Kanji; Magnetoencephalography; Semantic processing; Subtraction; Word perception

1. Introduction

Language related functions were the first to be ascribed to a specific location in the human brain and have been the subject of intense research for over a century. A `classical model' of language organization based on lesional studies proposes a frontal `expressive' area for planning and executing speech and writing movements, named after Broca, and a posterior `receptive' area for analysis and identification of linguistic sensory stimuli, named after Wernicke. Although many researchers have accepted this basic scheme, the cortical areas involved in language perception, however, have not yet been systematically characterized.

Of the thousands of languages all over the world, Japanese is one that is considerably different, since it has two separate but parallel writing systems, Kana and Kanji. The Kana phonograms are similar to alphabet based languages, and have only phonetic values. While each Kanji letter corresponding to the morphograms has a semantic, as well as a phonetic value. A few lesion studies pointed out that the left posterior inferior temporal gyrus (PITG) plays an important role in the Kanji reading and writing [9,13]. However, there have not been any additional systematic studies, thus these functions are still under discussion. A H$_2$O positron emission tomography (PET) study of Kanji processing reports that visually presented Kanji activates bilateral superior and inferior temporal regions, Broca's area and several other regions including the bilateral PITG [25]. PET results generally give information regarding the level of blood flow, glucose and oxygen consumption in the brain tissue but only indirectly yield functional information. Furthermore, such studies cannot provide sufficient temporal resolution to analyze the time course of neural activity. An electroencephalographic study of the Kanji processing was able to reveal a clear time course of signal changes in human brain [27]. The bilateral occipital lobes and the posterior temporal lobes revealed two major
peaks between 100 and 200 ms and around 300 ms after the stimulation onset. However, it was hard to clearly localize the sources of these responses because generated electric currents are distorted by the different conductivities of the skull, the brain, and inhomogeneities in the head.

Magnetoencephalography (MEG) reflects intracellular electric current flow in the brain and allows accurate localization of equivalent current dipole sources of the cerebral neural activity. Recently developed large scale MEG systems covering a substantial area of the head or the whole head have been utilized for the analyses of higher brain functions [16,26]. In this study, we measured event-related evoked magnetic fields to visually presented Kanji and meaningless figures and localized the activated brain regions using a 37 × 2 channels MEG system. In order to identify the significant cognitive activities, the MEG signals obtained with meaningless figure stimuli (reference) were subtracted from those obtained with the Kanji stimuli. This subtraction method has been frequently used for other functional neuroimaging techniques such as PET, functional MRI and EEG [3,21,27]. The functional activity associated with early sensory processing and motor movement can be removed from the image, allowing the identification of brain activity specific to one of the tasks. Thus, the regions showing such task specific changes are believed to participate more actively in one task than the other. If feasible, this task subtraction technique could become a powerful tool for the investigation of cognitive functions.

The final objective of the study is to visualize the flow of functional information within the human brain during visual perception and semantic process of the Kanji letters.

2. Subjects and methods

2.1. Subjects

Five native speaking Japanese subjects (Japanese speaker) between 28 and 40 years of age and five native speaking German subjects (German speaker) between 28 and 37 years of age who did not know any Japanese letters participated in this study. They were all strongly right-handed, as confirmed with the Edinburgh Handedness Inventory (laterality quotient was more than +85) [20] and were assumed to be normal or above in reading skills and general intelligence. Informed consent was obtained from each subject.

![Fig. 1. Magnetic response to silent Kanji (solid lines) and meaningless figures (broken lines) reading in the left hemisphere of a native Japanese (ooa) and a German (mka) speaker. Positive and negative deflection indicates the field outward and inward from the skull, respectively.](image)
Fig. 2. Subtracted results and contour maps of a native Japanese speaker (osa). (A) The subtraction responses (Kanji—meaningless letters) on the same base line. (B) Isocontour maps at 245 ms (B) and 535 ms (C) after the stimulus onset of the left (upper) and the right (lower) hemispheres. Solid and broken lines indicate the outward and inward magnetic flux from the head, respectively. The contour step is 10 fT.
2.2. Stimulation

Fifteen Kanji letters (KA_L) were selected from those learned during the first 6 years of a normal elementary school education. Criteria were such that each Kanji letter was grammatically a noun and had only one meaning so that every Japanese speaker would have identical interpretations. Fifteen meaningless figures (ML_F) were made by deforming the Arabian letters. These two different kinds of stimuli were matched for brightness and duration. Six hundred stimuli (300 times of KA_L and 300 times of ML_F) were presented with an 800 ms exposure time with inter-stimulus interval ranging from 1600 and 1800 ms. Each letter was approximately 8 cm × 8 cm in size and projected on a screen 100 cm in front of each subject’s face using 200,000 glass fibers. The order and number of the stimuli were counterbalanced over subjects. The room light was darkened throughout the MEG data acquisition.

The volunteers received instructions and brief practice sessions prior to starting of the measurement. All subjects were instructed to gaze at the center of the screen and not to move their eyes. The Japanese speakers were asked to silently read each Kanji letter and then imagine the object for that letter. When a meaningless figure was presented, they distinguished it from KA_L and specified it as ‘no Kanji’ in their mind. The German speakers who could read neither Kanji letters nor meaningless figures, were briefly trained to distinguish both of them and instructed to specify them as ‘Kanji’ or ‘no-Kanji’ in their mind to avoid loosing their attention.

2.3. Magnetoencephalography

Neuromagnetic evoked fields (NMEF) were measured in a magnetically shielded room using a 2 × 37 channel biomagnetic system, (Magnes II, Biomagnetic Technologies, San Diego, USA). Each subject lay on a bed with the head fixed between the two MEG dewars. Eye movements were monitored with an electrode below the left eye and a bipolar supraorbital to external canthal montage. Both dewars with each 37 sensors covered the temporoparietal regions bilaterally. Before the measurement, the accessible surfaces of the subject’s head were scanned by an electromagnetic digitizer (Polhemus, Model Isotrak, Colchester, VT, USA) to register the head and MEG sensor positions.

Each epoch of 1200 ms duration was time-locked to the visual stimulus onset and collected with a digital sampling rate of 520.8 Hz/channel. After acquisition, the obtained data were notch filtered digitally at 50 Hz and epochs
containing large artifacts (> 100 μV in the EMG) due to eye movement were manually discarded. The selected epochs with KA_L and ML_F stimuli were separately averaged and then digitally filtered using a 1–45 Hz bandpass filter with a steep rolloff (slope of 40 dB/Hz and flat from 1 to 45 Hz). The waveform in the 100 ms prestimulus period served as a baseline.

2.4. Source localization

The NMEF obtained with ML_F stimuli were subtracted from those obtained with KA_L stimuli since we focused our attention on the NMEF specific to the perception responses to Kanji letters. The peaks showing a clear polarity reversal and lasting more than 20 ms were manually selected as real perception responses on the basis of the previous electro-magnetoencephalographic studies [6,16]. The source locations of NMEF in the right and left hemispheres were separately determined from the 37-channel fields recorded over each hemisphere.

Six parameters (three coordinates: x, y and z and three current vectors: Q_x, Q_y and Q_z) of an equivalent current dipole were calculated every 2 ms on each selected segment using the single equivalent current dipole model with a locally fitted sphere as a head model. After the single equivalent current dipole estimation only dipoles with a correlation value of more than 0.9 between the measured and the calculated field distribution were considered for further analysis.

Although only the responses with one polarity reversal of the magnetic fields were selected, there was still the possibility that two or more sources existed in other brain areas. Therefore we used in addition a current density reconstruction method which can resolve multiple sources active at the same time: the current localization by spatial filtering (CLSF) [8,24]. The principle of the CLSF is to distinguish brain sources by their respective signal differences in space. This is accomplished by constructing a set of spatial filters for each of 6000 voxels (typical) of the analyzing space. These filters accept only the source activity originating from the corresponding voxel while attenuating the activity from all other voxels. The analyzing space is a sphere containing 6000 individual voxels of equal size. The location and the diameter of the analyzing sphere is adjusted to the brain volume where activity should be analyzed. When evaluating both MEG probes (2 × 37 channels) together the whole brain is selected. Using 6000 voxels a spatial resolution of approximately 7 mm results. The spatial filter coefficients for a given voxel

Fig. 4. Representative source locations of the early response (REJ) of a native Japanese speaker (ooa) calculated by the single equivalent dipole model (A) and the CLSF (B).
are obtained by weighting the forwardly calculated field distribution of a dipolar test source in the given voxel with the covariance statistics of the ‘a posteriori’ MEG signal. During the CLSF analysis two separate time intervals were selected for the calculation of the covariance matrices. For the localization of the early responses the interval was chosen between 0 and 350 ms after the stimulus onset and for the localization of the late responses the interval was chosen between 350 and 800 ms. Precautions to minimize the noise contribution to the covariance matrix were taken according to a procedure proposed by Robinson [23] where the smallest singular values are omitted in ascending order until the virtual sensor noise is low enough. Since the covariance matrix will be applied over the analyzing time of 350 ms for the early responses and 450 ms for the late responses, it emphasizes coherent and predominant signal components and attenuates uncorrelated signals (noise). Given this information for each voxel the measured magnetic field is treated by this set of spatial filters for each time instant yielding the source activity within each voxel. Detailed descriptions of the CLSF method have been described elsewhere [8,24,28]. An additional signal to noise improvement will be reached by a temporal integration of the CLSF results around the peak of the response component 20 ms typically to be analyzed: the current density plot (CDP).

Three-dimensional magnetic resonance images (MRI) were obtained using a 1.5 T Magnetom GBS whole body scanner (Siemens, Erlangen, Germany). Three-dimensional images (3D FLASH) of the entire head were acquired to process the MEG data. The field of view was 250 mm × 250 mm with a 256 × 256 matrix size and a slab thickness of 230 mm, yielding transverse images of 1.8 mm effective slice thickness. The obtained 3D MRI data were reconstructed using a simple edge detection algorithm. In order to superimpose the MEG results on 3D MRI, the scanned head surface data set was fitted to the reconstructed MRI head shape using a surface fit program developed by our department. The accuracy of this transformation has been verified to be within 2 mm [14,15,29].

3. Results

3.1. Components of response

Several peak components were observed at latencies between 150 and 800 ms after the stimulation onset in the

<table>
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<th>Latency (ms)</th>
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<th>German subjects</th>
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<td>Right side</td>
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<td>FuG</td>
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<td>200–400</td>
<td>(245, 0.98)</td>
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<td>&gt; 600</td>
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<td>Left side</td>
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<td>&gt; 600</td>
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| Mean latency and the maximum correlation value of each response are demonstrated in brackets. The results of the current localization of spatial filtering are written in Italics. FuG = Fusiform gyrus. PITG = Posterior inferior temporal gyrus. AITG = Anterior inferior temporal gyrus. PoCG = Postcentral gyrus. SmG = Superior marginal gyrus. PSTG = Posterior superior temporal gyrus. PITG = Posterior inferior temporal gyrus. NL = not localized.
Japanese and German speakers. In certain parts of the peaks, dipolar distributions with positive (outward) and negative (inward) fields were observed, strongly suggesting a single equivalent current dipole. Prominent responses peaking at 150–200 ms were consistently observed over all the MEG channels in all the subjects though there were subject specific amplitude effects. Fig. 1 depicts the actual MEG recordings of the left hemisphere with KA_L and ML_F tasks in the Japanese and German speakers. The Japanese speakers clearly showed different responses in KA_L and ML_F tasks at later than 300 ms after the stimulation, whereas the responses of the German speakers were quite similar and showed little differences between both tasks.

Fig. 2 is the subtraction result (KA_L − ML_F) of a Japanese speaker (ooa), showing the 37 × 2-channel MEG recordings on the same baseline position. The amplitude of the left side responses were generally greater than that of the right side responses. The right-side response peaked at 245 ms had high amplitude positive (outward from the scalp) and negative (inward) fields, demonstrated a clear polarity reversal, while the left hemisphere showed complex magnetic fields at the same latency (Fig. 2B). In Fig. 2C, the left hemisphere revealed a strong and clear polarity reversal at 535 ms after the stimulation.

The German speakers generally represented smaller amplitude responses in the subtracted NMEF than the Japanese speakers (Fig. 3). A clear polarity reversal was found only in the right hemisphere within 300 ms after the stimuli (right early component of the German speaker; REG) in four of five German speakers. One of them did not show any polarity reversal at all.

3.2. Source localizations

The summarized results in the Japanese speakers indicated that the right hemisphere activities (REJ sources) in the medial part of the posterior inferior temporal region were mostly located in the fusiform gyrus (FuG) (Fig. 4 and Table 1). Although several different regions such as the posterior superior temporal gyrus (PSTG) and superior marginal gyrus (SmG) sporadically showed activities in the late phase (right late component of the Japanese speaker; RLJ), the early components (<400 ms) were frequently seen in the fusiform gyrus (FuG) in three of the Japanese speakers (right early component of the Japanese speaker; REJ). The latency of REJ varied from 200 to 330 ms (median ± S.D.; 273.3 ± 50.7 ms). The sources of the left late component of the Japanese speaker (LLJ) sources were concentrated in the posterior part of left superior

![Fig. 5. Representative source locations of the late response (LLJ) of a native Japanese speaker (ooa) calculated by the single equivalent dipole model (A) and the CLSF (B).](image-url)
temporal gyrus (STG) and SmG with a mean latency of 616.1 ± 105.5 ms (Fig. 5).

In the German speakers, the REG source was located in the inferior portion of the occipito-temporal region around the FuG. The latency of REG varied from 220 to 270 ms (245 ± 23.8 ms) (Table 1). The right-hemisphere activity of the REG was quite similar to that of the REJ. However, the left-hemisphere dominance in the late component and RLJ were specifically observed only in the Japanese speakers.

The CLSF analysis localized identical regions that were determined also using the single equivalent dipole model (Figs. 4 and 5). Additional activations of the left PITG were found only in 2 of 5 Japanese speakers (Table 1). The distinct source areas were denoted by REJ and REG in the right FuG and LLJ in the left STG and SmG.

4. Discussion

The source localizations of human brain functions related to silent reading have been investigated using PET [12,21], functional MRI (fMRI) [11] and MEG [5,16,26]. It is noteworthy that MEG has better temporal resolution in the order of 1 ms, which is not the case in PET or fMRI technology, and provides complementary information concerning neural activity.

We observed two major responses to KA_L in all the Japanese speakers. The source of REJ appeared at approximately 270 ms in the right FuG and LLJ was seen in the left SmG or STG at about 600 ms after the stimulus onset, while the German speakers who recognized both of KA_L and ML_F as meaningless signs revealed only REG in the right FuG at the similar latency with REJ. Since the earlier responses were frequently represented in the right FuG in both of the Japanese and German speakers, it was suggested that the earlier response might reflect the perception and visual analysis of the presented objects and the right medial temporal lobe is likely to be involved in graphical recognition [4]. On the other hand, the left STG and SmG gave rise to the characteristic activity of the later response only in the Japanese speaker. We speculated that the special semantic processing of the Kanji is reflected by LLJ and the cortical regions including STG and SmG might play a major role in semantic processing.

Evoked potential measurements of epilepsy patients showed responses at 200 ms (N200) in the posterior part of the FuG to the visual presentation of faces, which is compatible with REJ and REG in our study [1]. Letter-strings and Arabic numbers also evoked similar N200s in the same regions [2,19]. This N200 has been considered to reflect automatic stages of category-specific processing. In fact, the N200s were insensitive to word type, whereas longer-latency potentials recorded from the superior temporal gyrus and the Broca’s region were highly sensitive to word types [19]. Thus, it is plausible that the early responses in the FuG might reflect the visual perception processes of drawing, lines and the structure of KA_L and ML_F.

Face recognition and memory related tasks show right-side dominance in FuG responses, but letter-strings mainly activate the left side [10,22]. The reason for these differences is still unclear. However, it has been argued that faces are an important category of objects for which rapid recognition is required [30]. Perhaps the FuG activity associated with face encoding reflects the detection of novelty and the encoding of an unfamiliar face’s unique configuration. ML_F was not familiar to the Japanese or German speakers, so there was strong demand on memory-related recognition and the analysis of the structure and visual attention, which activated the right FuG, similar to the face recognition task.

The standard neurological reading model is that visual word forms are accessed and transformed into an auditory form in the left angular gyrus, and thereafter recognized as words in Wernicke’s area [7]. In the previous EEG studies, late negative event related potentials called ‘N400’ have been observed in experiments that required subjects to make decisions about visually presented words based on their semantic attributes [17,18]. Kuriki et al. [16] investigated the Japanese speakers and observed the activated left STG and SmG at latencies of approximately 400 ms by MEG when the phonological Japanese letters (Kana) were presented. In our study, the late component sources in the periods of 480–790 ms were concentrated mostly in the posterior part of the left superior temporal region. The German speakers who only could categorize both of the stimuli since they did not know the Kanji meaning, revealed no response in the latter components. Given the left hemisphere dominance in the Japanese speakers and no activity in the German speakers, it is reasonable to conclude that the later responses in the STG and SmG are likely the neural basis of the semantic processing of the Kanji characters.

Although this MEG study did elicit the various regional activities in RLJ or left PITG activity in two of the Japanese speakers by the CLSF analysis, these results were not uniformly observed in all of the Japanese speakers. Regional cerebral blood flow was measured by PET with the H15O injection to study the changes during Japanese Kanji reading [25]. In addition to the right FuG, the left STG and SmG activities, they strongly suggested that the bilateral (left-side dominant) PITGs, the inferior frontal lobe (Broca’s area), right temporal region and several other regions have a possibility of participating the Kanji recognition. Although the reasons for this discrepancy are not understood, several methodological reasons can be considered. The frontal region was out of MEG sensitivity since our MEG sensors were not applied on the bilateral frontal regions in order to avoid the artifacts associated with eye movements. The involuntary eye movements were frequently observed during ML_F presentation and especially...
in the Japanese speakers who tried to recognize ML_F. Furthermore, using two extremely different subject groups such as the Japanese and German speakers we could clearly delineate the most active regions for the semantic processing of Kanji. We believe that this technique can be applied to the analysis of other semantic processes and could be helpful in the identification of the dominant hemisphere, and becomes a powerful tool to elucidate the pathophysiology of aphasia and dyslexia in clinical setting.

Acknowledgements

This study was supported in part financially by the Alexander-von-Humboldt Foundation (Bonn, Germany) and the Marohn Foundation (Erlangen, Germany). We thank Dr. M. Wessinger for critical reading of the manuscript.

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