

# The Effect of Phonological Repetition on Cortical Magnetic Responses Evoked by Visually Presented Words

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## Abstract

■ Neuroimaging studies have reported that the left superior temporal cortical area is activated by visually presented words. In the present study, we recorded cortical magnetic responses evoked by visual words and examined the effect of phonological repetition (e.g., *bair-hare*) on left superior temporal cortical activity, using pairs of homophonic Japanese words as stimuli. Unlike English, Japanese has a large number of homophone pairs with a totally different orthography. By taking advantage of this feature of the Japanese writing system, the effect of phonological repetition can be solely examined without being confounded by the effect of orthographic similarity. Magnetic responses were recorded over the bilateral temporal sites of the brain while subjects silently read words. The words were presented one by one; a quarter of them was

immediately followed by a homophonic word. Clear magnetic responses in the latency range of 300–600 msec were observed in the left hemisphere, and the responses to the homophones were smaller than those to the first presented words. In the right hemisphere, clear responses were not consistently recorded in the same latency range, and no effect of phonological repetition was observed. The sources of the responses recorded over the left hemisphere were estimated to be in the left superior temporal cortical area adjacent to the auditory cortex and the source strength as well as the magnetic responses showed a reduction by phonological repetition. This result suggests that the activity in the left superior temporal cortical area is associated with access to the phonological representation of words. ■

## INTRODUCTION

Visual word recognition involves processing of the phonological form and semantic information of stimulus words. Both types of information are assumed to be stored in the mental lexicon as phonological and semantic representations of each word, and are retrieved automatically when one encounters a word (e.g., Coltheart, Curtis, Atkins, & Haller, 1993). Studies on patients with brain lesions have suggested that the processing of phonological information has a distinct neural base from that of semantic information (e.g., Miceli & Capasso, 1997; Morton & Patterson, 1980). For example, Caramazza and Hillis (1991) reported an aphasic patient who showed a normal comprehension of written words, but frequently made semantic errors in the oral reading of them (e.g., saying “money” in response to the word “dollar”). This symptom might be due to a selective impairment in accessing an appropriate phonological representation and suggests that phonological representations are stored independently from semantic representations in the brain. However, how the mental

lexicon is implemented in the cerebral cortex is still unclear.

Neuroimaging studies using positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and magnetoencephalography (MEG) have repeatedly demonstrated that the left superior temporal cortical area is activated when subjects read words (e.g., Simos et al., 2002; Fujimaki et al., 1999; Pugh et al., 1996; Salmelin, Service, Kiesilä, Uutela, & Salonen, 1996; Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995; Price et al., 1994). For example, Helenius, Salmelin, Service, and Connolly (1998) recorded magnetoencephalograms evoked by Finnish words in sentences and found a magnetic source activity in the left superior temporal cortical area. They reported that the activation in this area occurred in the latency range of 250–600 msec poststimulus, similar to the time window of the N400, a language-related component of event-related brain potentials (ERPs) (e.g., Kutas & Federmeier, 2000; Koyama, Nageishi, & Shimokochi, 1992).

Recently, left superior temporal activity has been found to be modulated by the repeated presentation of the same words (Dhond, Buckner, Dale, Marinkovic, & Halgren, 2001; Haist et al., 2001; Sekiguchi, Koyama, & Kakigi, 2000, 2001). For example, we recorded cortical magnetic responses evoked by Japanese words and

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found that the activity in this area became weaker for the repeated words, compared with that for the first presented words (Sekiguchi et al., 2000, 2001). This reduced activity might be the neural correlate of the word repetition effect reported in behavioral studies, that is, the improvement of reading performance for repeated words (e.g., Tenpenny, 1995). The behavioral word repetition effect is assumed to reflect the temporary change in the accessibility of word representations preexisting in the mental lexicon (Monsell, 1985; Forster & Davis, 1984). The MEG repetition effect thus suggests that the left superior temporal cortical activity is associated with the access to word representations. This view was further supported by the finding that the activity in this area was not modulated by the repetition of pronounceable nonwords having no corresponding representation in the mental lexicon (Sekiguchi et al., 2001).

In these studies, the type of representations processed in the left superior temporal area could not be determined because the phonological, semantic, and orthographic aspects of words are repeated at the same time. Studies using PET and fMRI have reported that the left superior temporal area is activated when subjects perform tasks requiring the phonological processing of written words, for example, rhyme matching (Pugh et al., 1996), vowel detection (Fujimaki et al., 1999), and pronunciation (Rumsey et al., 1997; Bookheimer et al., 1995; Price et al., 1994). The activation of this area has also been found when subjects listen to and try to identify spoken words, which requires access to the phonological representations of these words (e.g., Binder et al., 2000). It is thus probable that the left superior temporal cortical area is related to accessing the phonological representations of words, and the reduction in its activity is caused by the repetition of the phonological aspect of words.

The aim of the current MEG study was to examine an involvement of the left superior temporal cortical area in the phonological processing of words. We presented two homophonic words successively (e.g., *bair* and *bare*) and tested whether the repetition of word phonology modulates the left superior temporal activity evoked by visually presented words. On the assumption that a pair of homophonic words shares a single phonological representation, presentation of one word in a pair would make the shared phonological representation easier to access, and lead to a smaller cortical activity when the other word in the pair was accessed subsequently. Such a temporary modification of phonological representations has actually been suggested in behavioral studies as the facilitation of performance in word recognition tasks by phonological repetition (e.g., Grainger & Ferrand, 1994; Perfetti & Bell, 1991). Therefore, if the left superior temporal cortical area is related to accessing phonological representations, its activity would be reduced not only by the repetition of the same word as shown by the previous studies but

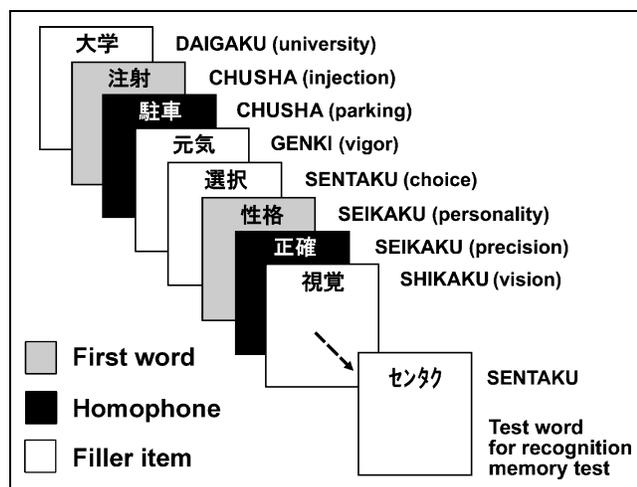
also by phonological repetition. In fact, in ERP studies, the phonological relation of two words has been reported to modulate an ERP component (e.g., Rugg, 1984). Because the spatial resolution of electroencephalography (EEG) is low due to the influences of volume currents and anatomical inhomogeneities, the cortical area responsible for this ERP phonological priming effect has not been determined. Compared with EEG, MEG has a better spatial resolution with millimeter-range precision (Hämäläinen, Hari, Ilmoniemi, Knuutila, & Lounasmaa, 1993) and, hence, enables one to examine the effect of phonological repetition on the left superior temporal cortical activity.

We used pairs of homophonic Japanese words as stimuli. Most English homophones are orthographically similar (e.g., *week* and *weak*) because of the high correlation between orthography and phonology. Hence, it is quite difficult to determine whether an obtained effect results from the phonological relation of stimuli or the additional orthographic relation, if English words are used for examining the phonological repetition effect. Unlike in English, there are a large number of homophone pairs differing in orthography in Japanese. Table 1 shows an example of Japanese homophone pairs. 正確 and 性格 have a phonemically and prosodically identical pronunciation, /seikaku/, but are written in different Kanji characters (Kanji is a Japanese morphographic script) (Koyama, Kakigi, Hoshiyama, & Kitamura, 1998; Iwata, 1984). By taking advantage of this feature of the Japanese writing system, the effect of phonological repetition can be solely examined without being confounded by the effect of orthographic similarity.

We recorded cortical magnetic responses from Japanese subjects while they silently read Japanese Kanji words. The stimulus words were presented one by one, a quarter of them followed by a homophone (see Figure 1), and the magnetic responses to the first-presented words (hereafter called first words) and those to homophonic words (homophones) were compared. If left superior temporal cortical activity is associated with phonological accessing, a reduction in the activity will be observed for the homophones. On the other hand, if this activity is related to accessing semantic or orthographic rather than phonological representations, it will not be modulated by phonological repetition. The magnetic responses were recorded using dual

**Table 1.** Example of a Japanese Homophone Pair

|                     | Homophone Pair |             |
|---------------------|----------------|-------------|
| Orthography (Kanji) | 正確             | 性格          |
| Pronunciation       | /seikaku/      | /seikaku/   |
| Meaning             | Precision      | Personality |



**Figure 1.** An example of a stimulus presentation sequence. A first word, shown on a gray card, was immediately followed by a word having the same pronunciation (homophone, shown on a black card). All of the stimulus words were written in Japanese Kanji script. The pronunciation and meaning of the words are shown on the right. In the recognition memory test, a test word written in Katakana script was presented, and subjects were required to judge whether or not the word appeared in the block.

37-channel axial gradiometers placed over the bilateral temporal sites. The subjects were not required to provide any overt responses. The attention to the stimuli was ensured by a recognition memory test performed every 20 trials.

## RESULTS

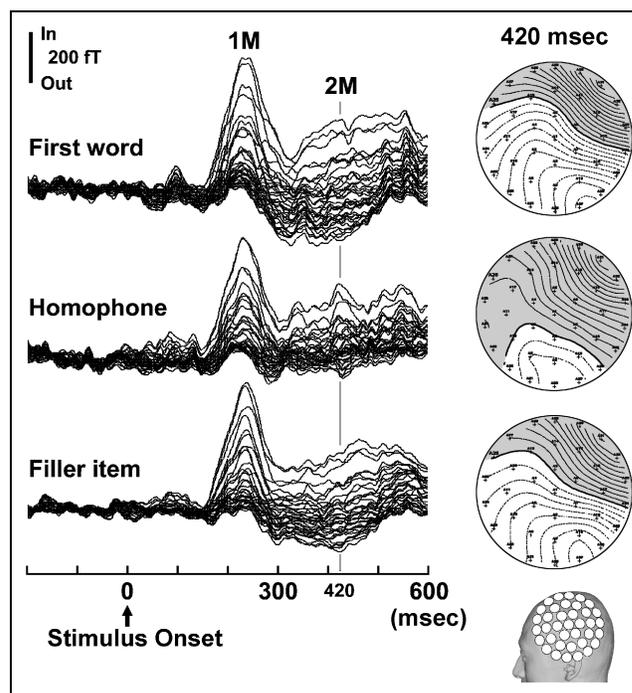
### Magnetic Responses

Figure 2 shows representative waveforms of the magnetic responses recorded over the left hemisphere from one of the 15 subjects. In the left hemisphere, two components were observed in all the subjects except for four subjects mentioned below, the first component persisting from approximately 150 to 250–300 msec poststimulus and the second component ranging from 300 to 500–600 msec (for simplification; hereafter we refer to the first component as 1M and the second component as 2M). In the right hemisphere, only the 1M component was consistently observed across the subjects. In the left hemisphere, the amplitude of the 2M component for homophones was smaller than that for first words. The amplitude of the 2M component was also reduced for homophones compared with that for filler items that were not preceded by their homophonic words. The isomagnetic field maps of the 2M component have the flux directed outward on one side and inward on the other, suggesting that the source activity of this component was located below the sensors in all conditions.

Figure 3 shows the magnetic strength averaged in the latency range of 300–600 msec (2M) in each of the

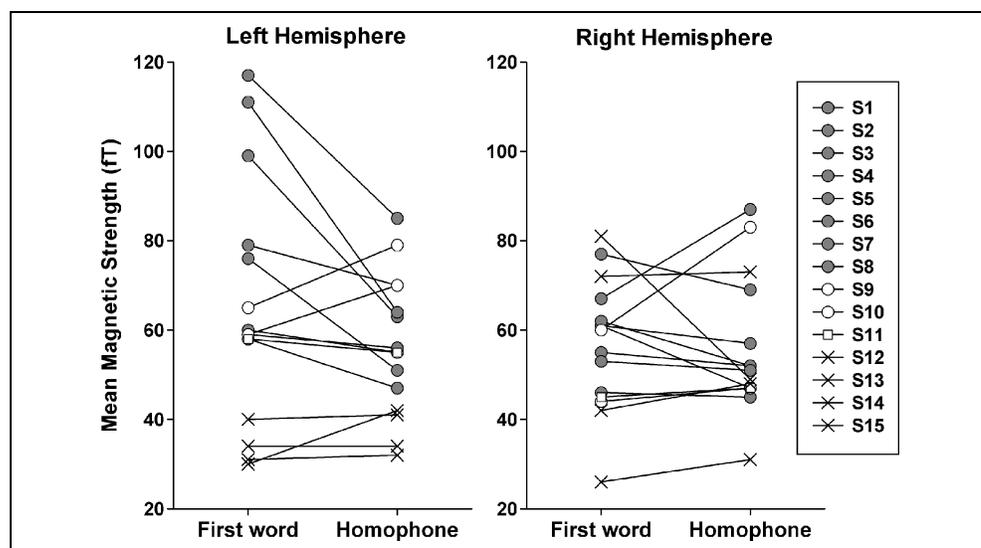
15 subjects. The magnetic strength was measured with the standard deviation (*SD*) of the recorded responses across 37 channels at each time point (e.g., Sekiguchi et al., 2001; Koyama et al., 2000). In four subjects shown by crosses (subjects S12–S15), the magnetic responses recorded over the left hemisphere showed no or only a small deflection in the latency range of 300–600 msec, although in two of them reliable deflections were recorded over the right hemisphere. In these subjects, the mean magnetic strength in the left hemisphere was less than 42 fT and less than three times the mean magnetic strength in the baseline period (200 msec before stimulation). Because we were interested in the activity in the left hemisphere, these data were not used for further analysis. In the remaining 11 subjects (S1–S11), on the whole the mean magnetic strength in the left hemisphere was reduced by the phonological repetition, although two reversed patterns were observed (S9 and S10).

Figure 4 shows the magnetic strength averaged across the 11 subjects. The effect of phonological repetition was observed only in the left hemisphere in the latency range of 300–600 msec poststimulus. For statistical analyses, the magnetic strength was averaged for each



**Figure 2.** An example of magnetic responses evoked by first words, homophones, and filler items recorded over the left hemisphere in one subject (S4). The waveforms of 37 channels are superimposed. Two sustained components (termed 1M and 2M) were identified in the magnetic responses. The amplitude of the 2M component was reduced by phonological repetition. The isomagnetic field maps of the magnetic responses at 420 msec (2M component) are shown beside each waveform (contour step is 20 fT). The shaded area illustrates magnetic flux out of, and the white area into, the skull. The approximate locations of the 37 sensors are shown in the inset as white circles.

**Figure 3.** The strength of magnetic responses averaged in the latency range of 300–600 msec (2M) in each subject. Gray circles indicate the subjects in which a source was estimated to be in the left superior temporal cortical area in source analyses, and open circles indicate the subjects in which it was not. Squares indicate the subject in which the left superior temporal source was obtained only for homophone data. Crosses indicate the subjects whose data was not used for further analysis because the magnetic responses recorded over the left hemisphere were too small.



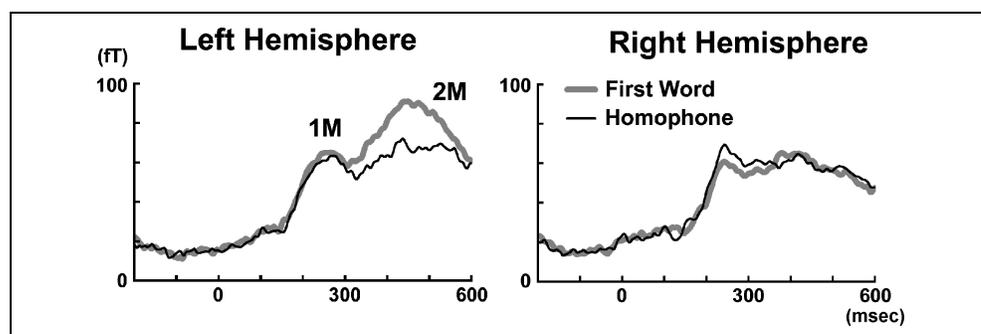
subject in two latency ranges: 200–300 msec (1M) and 300–600 msec (2M). The averaged values were analyzed by two-way analyses of variance (ANOVAs) using stimulus type (first word/homophone) and hemisphere (left/right) as repeated measure factors. The significance level was set at .05. In the latency range of 200–300 msec, the analysis showed no effect of stimulus type,  $F(1,10) < 1$ , or interaction,  $F(1,10) = 3.35$ ; that is, the phonological repetition did not modulate the strength of the 1M component. In the latency range of 300–600 msec, the ANOVA showed a significant interaction between stimulus type and hemisphere,  $F(1,10) = 8.18$ ,  $p < .05$ . The post hoc one-way ANOVA for the left-hemisphere data showed that the magnetic responses to homophones were significantly smaller than those to first words,  $F(1,10) = 5.10$ ,  $p < .05$ . In contrast, the one-way ANOVA for the right-hemisphere data did not show a significant difference between the responses to first words and to homophones,  $F(1,10) < 1$ . The same results were obtained when the root mean square (RMS) of the recorded responses across 37 channels was used as an index of the magnetic strength. The analysis for the 1M component did not show any effect of stimulus type,  $F(1,10) = 1.42$ , or interaction,  $F(1,10) = 1.61$ , and the

analysis for the 2M component showed a significant interaction between stimulus type and hemisphere,  $F(1,10) = 5.24$ ,  $p < .05$ , showing that the phonological repetition selectively reduced the magnetic responses recorded over the left hemisphere.

### Source Analysis

A multidipole source analysis using BESA (Scherg, 1992) was conducted for the 2M components recorded over the left hemisphere. The first-word data and homophone data were analyzed separately. We accepted only the sources for which the percentage of the residual variance (%RV) between the observed fields and the theoretical fields was below 10%. The latency ranges in which the phonological repetition effect was observed differed among subjects, although they were within the range of 300–600 msec. Furthermore, the peak latencies of the 2M component also varied across subjects from 401 to 533 msec (on average  $465 \pm 49$  msec). Because the aim of the source analyses was to determine the cortical area whose activity is responsible for the phonological repetition effect, we analyzed the periods of the responses covering both the peak of the 2M

**Figure 4.** The strength of magnetic responses (SD values) averaged across 11 subjects. The magnetic responses recorded over the left hemisphere were reduced for homophones in the latency range of 300–600 msec poststimulus.



component and the latency range in which the phonological repetition effect was remarkable. The following periods were actually used: 350–550 msec (7 subjects), 350–500 msec (2 subjects), and 400–550 msec poststimulus (2 subjects).

In all 11 subjects, sources with a %RV below 10% were obtained for both the first-word and homophone data. In nine subjects, two sources explained more than 90% of data variance, and in two subjects, three sources did. The number of estimated sources was the same between the first-word and homophone data in each subject. In 8 of the 11 subjects (S1–S8), a source was estimated to be in the left superior temporal cortical area mostly adjacent to the auditory cortex. Figure 5A shows the location of the left superior temporal source in one subject (S1), superimposed on the MR image surface renditions, and Figure 5B summarizes the locations of the estimated sources in two- or three-dipole models for all 11 subjects' data (first-word data). The circles in Figure 5B represent the eight sources estimated to be in the left superior temporal cortical area. They were in the inferior bank of the left sylvian fissure or near the superior temporal sulcus. In two subjects (S9 and S10), no source was found in the left superior temporal cortical area. Their data did not show a reduction of magnetic responses with phonological repetition, as represented in Figure 3 by open circles. For subject S11 (squares in Figure 3 and Figure 5B), the left superior temporal source was not found in the first-word data but was found in the homophone data.

The locations of the left superior temporal sources were similar across the first-word and homophone data. The difference in the source location was less than 15 mm (on average  $9 \pm 5$  mm). The current strength of the left superior temporal sources was then compared between the first-word and homophone data. The mean current strength in the latency range of 300–600 msec was significantly reduced by the phonological repetition,  $F(1,7) = 14.99$ ,  $p < .01$ . In source modeling, the strength of a deeper source is inevitably estimated to be greater than that of a shallower source that explains the same magnetic fields (Hämäläinen et al., 1993). Thus, there is a possibility that the observed phonological repetition effect in the source strength is actually due to the difference in the depth of the estimated sources. In fact, the  $y$  values (left–right axis) of the source location for first-word data (on average  $47 \pm 3$  mm) were smaller than those for homophone data ( $49 \pm 7$  mm), meaning that the former were located deeper than the latter, although there was no significant difference between them,  $F(1,7) = 1.37$ . To exclude this possibility, the sources estimated for the first-word data were applied to the homophone data. The source strength of the homophone data was then recalculated. The %RV of the first-word sources for the homophone data was less than 15%. Figure 5C shows the time behavior of current strength of the left superior temporal sources. The current strength for the homophones is superimposed on the strength for the first words, using the same sources. The current strength for the homophones was

**Figure 5.** The results of multidipole source analyses. (A) An example of the sources estimated to be in the left superior temporal cortical area (Subject S1, first-word data). The source location was superimposed on the MR image surface renditions. (B) The locations of the sources collected from 11 subjects. The sources for the first-word data were plotted on a schematic brain with the help of individual MR images in which each source was superimposed. These sources were projected on the surface of the brain to facilitate visualization. The circles represent the sources estimated to be in the left superior temporal cortical area, and the triangles represent the sources in the other cortical areas. The gray marks represent the sources in which the mean current strength (300–600 msec) showed a more than 10% reduction with phonological repetition. The open marks indicate the sources in which the current strength was not reduced. The sources in the left superior temporal cortical area showed a consistent reduction in current strength. The squares indicate the sources in which a comparison was not made because different source locations were estimated between first-word and homophone data. (C) The time behavior of the current strength of the left superior temporal (ST) source, represented by circles in Figure 5B, for each subject (S1–S8).

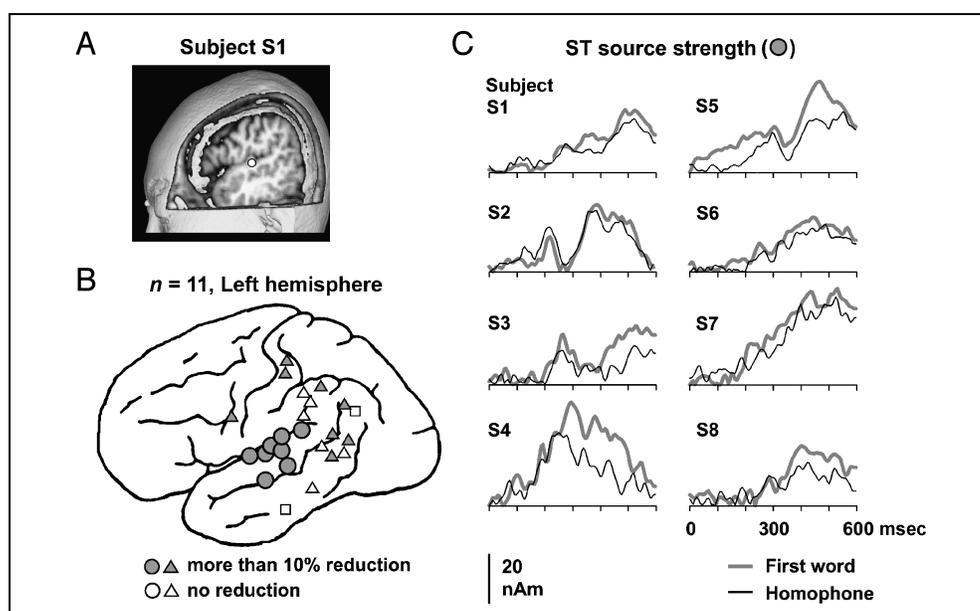


Figure 5C shows the time behavior of current strength of the left superior temporal (ST) source, represented by circles in Figure 5B, for each subject (S1–S8). The current strength for the homophones is superimposed on the strength for the first words, using the same sources. The current strength for the homophones was

smaller than that for the first words in all of the eight subjects. The mean current strength in the latency range of 300–600 msec was reduced by  $28 \pm 13\%$  on average, and a one-way ANOVA showed that this effect was significant,  $F(1,7) = 24.57, p < .01$ .

The statistical analysis for the location of the left superior temporal sources showed a significant difference in  $x$  values (anterior–posterior axis),  $F(1,7) = 7.64, p < .05$ , between the first-word and homophone data, but not in  $z$  values (top–bottom axis),  $F(1,7) = 4.00$ , or  $y$  values. The locations of the left superior temporal sources for homophones were on average 5 mm anterior to those for first words. The source location means the center of gravity of a synchronously active neuronal population. The center of gravity may shift anteriorly when neuronal activity in the posterior part of an activated cortical area is reduced. Hence, the anterior shift of the source location for homophones might reflect that the posterior part of the cortical area activated by first words was reduced.

In Figure 5B, the sources in areas other than the superior temporal cortical area are shown by triangles. Their locations were varied over a wide range of cortical areas, including the inferior parietal, frontal, posterior temporal, and inferior temporal cortical areas. The locations of these sources were also similar between the first-word and homophone data, except for subject S11, with the difference being less than 17 mm (on average  $9 \pm 5$  mm). The strength of these sources was also compared, applying the sources for the first-word data to the homophone data. The gray triangles in Figure 5B represent the sources in which the mean current strength in the latency range of 300–600 msec showed a more than 10% reduction with phonological repetition. The open triangles indicate the sources in which the mean current strength showed no reduction. The reduction in current strength was observed in the posterior-temporal and parietal sources, but the effect was not consistent across the subjects.

## DISCUSSION

We examined whether the left superior temporal cortical activity evoked by visually presented words is modulated by the repetition of word phonology. Subjects read Japanese Kanji words, some of which were followed immediately by homophonic words. The magnetic responses to homophones were smaller than those to first words. This effect of phonological repetition was observed in the responses recorded over the left hemisphere in the latency range of 300–600 msec (2M component). In 8 of the 11 subjects, the magnetic source activity for this component was estimated to be in the left superior temporal area mostly adjacent to the auditory cortex. The current strength of these sources showed a reduction with phonological repetition. In the

right hemisphere, a clear response was not consistently recorded in the same latency range, and no effect of phonological repetition was observed in any latency range.

In the present study, first-words and homophones were not similar either orthographically or semantically. The reduction in left superior temporal cortical activity was thus solely attributable to the repetition of word phonology. Hence, this result suggests that the left superior temporal cortical area is related to the processing of word phonology. Recent MEG studies have also implied a functional association between the left superior temporal cortical area and phonological processing. Pylkkänen, Stringfellow, and Marantz (2002) reported that the latency of M350, which was a magnetic response component elicited by visual words in the left temporal cortex peaking at 300–450 msec poststimulus (Pylkkänen & Marantz, 2003), was sensitive to the phonotactic probability of stimulus words (i.e., the frequency that a particular segment or sequence of segments will occur in spoken words). Wydell, Vuorinen, Helenius, and Salmelin (2003) reported that the duration of left superior temporal activity (latency range 200–600 msec) was longer for long letter strings than for short letter strings. They interpreted this effect as arising from on-line phonological processing. PET and fMRI studies have also suggested that this area is related to phonological processing (e.g., Fujimaki et al., 1999; Pugh et al., 1996). For example, Rumsay et al. (1997) reported that the left superior temporal gyrus near the auditory cortex was activated by the pronunciation of written words, but not by a word–nonword judgment in which the phonological processing is less important. The present study demonstrated the involvement of the left superior temporal cortical area in phonological processing in a more straightforward way using the phonological repetition paradigm.

The present study further showed that the phonological processing in visual word recognition occurs in the latency range of 300–600 msec after word onset. This timing is consistent with the finding in ERP studies investigating the cross-modal repetition priming effect. Rugg, Doyle, and Melan (1993) reported that the repeated presentation of visual words modulates the amplitude of ERPs from approximately 200 msec poststimulus, whereas word repetition across auditory to visual modalities modulates the ERP amplitude from approximately 300–350 msec poststimulus. They argued that the early visual–visual effect occurs at the orthographic level, and the late auditory–visual effect reflects the phonological processing, common to both visual and auditory word recognition. The reduction of cortical activities and its latency range are also consistent with the phonological priming effect on ERPs. Rugg (1984) reported that the amplitude of a negative deflection to target words, peaking around 450 msec, was smaller for rhyming words than nonrhyming ones.

In our previous study (Sekiguchi et al., 2001), the activity in the left superior temporal cortical area was reduced by repeated presentation of the same word but not by the repetition of pronounceable nonwords that are dissimilar to any real words. The crucial difference between words and nonwords is that the former has corresponding representations in the mental lexicon whereas the latter do not. This result was interpreted as indicating that left superior temporal cortical activity is associated with access to word representations stored in the mental lexicon. Recently, Embick, Hackl, Schaeffer, Kelepir, & Marantz (2001) reported that the peak latency of the M350, probably corresponding to our 2M component, was sensitive to word frequency. A PET study also reported that left superior temporal activity is modulated by word frequency (Fiez, Balota, Raichle, & Petersen, 1999). Because word frequency is considered to affect the accessibility of word representations (e.g., McClelland & Rumelhart, 1981), these findings also suggest that left temporal cortical activity is related to accessing the mental lexicon. Considering these findings together with the present results, the reduced activity in our previous studies might be caused, at least in part, by the repetition of phonology, and the left superior temporal cortical area might be involved in accessing phonological word representations.

Regarding the role of phonological representations, two usages are assumed in the psychological literature (e.g., Monsell, 1987). One is “output” use; that is, the phonological representations are used for correct pronunciation of visual words, in particular for reading of irregular words (e.g., *pint* in English and most Japanese Kanji words) that have a pronunciation incongruent with letter-to-sound rules (Coltheart et al., 1993). The other is “input” use; that is, the phonological representations are matched with an internal phonological code decoded from orthography, like the processing in hearing spoken words. In recent psychological studies, this process has been assumed to be important for the access to semantic information of both English (e.g., Lesch & Pollatsek, 1998; Van Orden, 1987) and Japanese Kanji words (e.g., Sakuma, Sasanuma, Tatsumi, & Masaki, 1998). Although it is difficult to determine which process is associated with left superior temporal activity (and even whether these processes are separated in the brain) solely from the present results, we consider the latter usage is more plausible. A number of brain imaging studies have shown that this area is activated in response to hearing spoken words (e.g., Binder et al., 2000; Petersen, Fox, Posner, Mintun, & Raichle, 1989) and to “hearing” imagined speech in the mind (McGuire et al., 1996). These findings suggest that the left superior temporal area is related to the processing of incoming phonological information. In the present study, the subjects were asked to pronounce the stimulus words silently, and thus are likely to “hear” the word sound internally. The left superior temporal activity might be

associated with this input use of the phonological representations in reading.

In behavioral studies, the repetition of word phonology has been shown to facilitate the recognition of visual words (e.g., Grainger & Ferrand, 1994; Perfetti & Bell, 1991). The facilitatory effect of phonological repetition is also reported in Japanese studies on Kanji words in both pronunciation (Ishii, 2000) and lexical decision tasks (Matsuda, 1998). These effects of phonological repetition are often explained by a temporary change in the accessibility of phonological representations (e.g., Grainger & Ferrand, 1994); the repetition priming effect has been explained likewise. Specifically, the first word and its homophone share the same phonological representation, and because the activation induced by the first word remains in that representation for some period, access to this representation is easily achieved when the homophone is presented (“activation” is a metaphorical expression of lexical access used in psychological models and does not directly correspond to neural activation). The reduced activity of the left superior temporal cortical area for homophones might reflect that their phonological representations have been made easier to access by the prior presentation of first words. Alternatively, the effect of phonological repetition resulted from rehearsal of the first words. In this study, the subjects performed a recognition memory test at the end of each block. Although they were required to refrain from rehearsing stimulus words, it is likely that they violated this instruction to improve their memory performance. Hence, there is a possibility that the left superior temporal activity was modulated because a first word was repeated and heard in mind just before or simultaneously with the presentation of the homophone. In either case, the reduction in left superior temporal activity might be caused by the easy access to the phonological representation of the homophone because of prior processing of the phonological information it conveyed.

Recent MEG studies have shown that the activity in the left superior temporal cortical area is also modulated by semantic factors (e.g., Halgren et al., 2002; Suzuki et al., 2001; Simos, Basile, & Papanicolaou, 1997). For example, Helenius et al. (1998) reported that the left superior temporal cortical activity evoked by visual words that are semantically congruent with their sentential context (e.g., *The piano was out of / TUNE*) was smaller than that evoked by incongruent words (e.g., *The pizza was too hot to / SING*). Our previous study (Koyama, Naka, & Kakigi, 1999) showed that the left superior temporal cortical activity was also reduced by semantic priming. In this study, the former part of a Japanese idiom (prime) and the latter part (target) were shown to the subjects in succession. Some targets were preceded by inappropriate primes that do not make up existing idioms with the targets. The left superior temporal cortical activity in response to the target preceded

by its prime was remarkably smaller than that evoked by the target preceded by an inappropriate prime. These findings suggest that the left superior temporal cortical area is related to semantic processing.

Considering the above findings, the left superior temporal cortical area might be involved in both phonological and semantic access. A similar view has been proposed in studies using other neuroimaging techniques (Fujimaki et al., 1999; Pugh et al., 1996). Whether, and to what extent, the area related to phonological access and that related to semantic access overlap is unclear, however. Ojemann, Ojemann, Lettich, and Berger (1989) assessed the language areas by electrically stimulating the cortical surface. They reported that the language center was highly localized, forming several mosaics of 1 to 2 cm<sup>2</sup>. The mosaics were distributed in the left peri-sylvian region and there was substantial individual variability. Hence, the area related to phonological access and that related to semantic access might be discretely distributed in the left superior temporal cortical areas.

Alternatively, the reduced activity in Helenius et al. (1998) and Koyama et al. (1999) might reflect a change in phonological representations, not in semantic representations. In these studies, subjects were able to anticipate stimulus words from the preceding contexts (Helenius et al., 1998) or the former part of idioms (Koyama et al., 1999), and thus the phonological representations of the anticipated words may have been activated before the actual presentation of these words. In Helenius et al., the left superior temporal cortical activity was also reduced for semantically appropriate but unexpected words (e.g., When the power went out, the house became / QUIET). Even in this case, it is probable that the phonological representation of a target word was activated subconsciously by virtue of its semantic representation being activated by the semantic context of sentences.

In a study of ERPs for auditory-presented words, Radeau, Besson, Fonteneau, and Castro (1998) reported that the amplitude of the scalp-recorded N400 component was attenuated more by the semantic relation of words than by the phonological relation. This finding suggests that the N400 is related not only to the phonological processing but also to the semantic processing. Because the left superior temporal area is suggested to be a source of the N400 (e.g., Helenius et al., 1998), this finding could support the view that this area has multiple functions. However, the N400 probably has multiple generators (e.g., Nobre & McCarthy, 1994), and intracranial recording studies have shown that bilateral anterior medial temporal lobes also contribute to the generation of the N400 (e.g., McCarthy, Nobre, Bentin, & Spencer, 1995). Recent studies using event-related fMRI have also suggested that the semantic congruency and semantic priming effects are related to the anterior medial temporal area (Rossell, Price, & Nobre, 2003;

Kiehl, Laurens, & Liddle, 2002) and the anterior middle temporal gyrus (Copland et al., 2003). It is therefore probable that the characteristics of the N400 reported in Radeau et al. (1998) reflected the characteristics of the other brain activity. Whether the left superior temporal activity is associated with multiple functions or a single function should be examined further. Direct comparison of the effects of phonological repetition/relation and semantic relation will answer this question.

In conclusion, we found that the activity in the left superior temporal cortical area was reduced by the phonological repetition of written words in the latency range of 300–600 msec poststimulus. Considering our previous finding that left superior temporal cortical activity is reduced by word repetition but not by non-word repetition (Sekiguchi et al., 2001), this area might be involved in access to the phonological representations of words.

## METHODS

### Subjects

Fifteen healthy, native speakers of Japanese (8 women and 7 men; age range 20–38 years) participated in the experiment. All subjects were right-handed (self-reported) and had normal or corrected-to-normal vision. The participants gave their informed consent, and the study was approved by the Ethical Committee of the National Institute for Physiological Sciences.

### Stimuli

The stimuli were 480 Japanese nouns. They were all two-Kanji character words that were pronounced with either three or four morae (a mora is a unit of rhythm in spoken Japanese usually consisting of a consonant and a vowel). The critical items for the present experiment consisted of 120 pairs of words with phonemically and prosodically identical pronunciations, that is, homophone pairs. The words in a pair did not share any Kanji characters and thus had no orthographic relation (see Table 1). They had little semantic relation either, which was confirmed by two of the authors (TS and SK). One member of each homophone pair was presented (first word), and the other member followed it immediately (homophone). The mean word frequencies were matched across the first words and the homophones according to a Japanese word frequency norm (National Language Research Institute, 1970). Furthermore, the assignment of words to these stimulus types was reversed for half of the subjects so that a first word to one subject appeared as a homophone (second word) to another. These manipulations prevented the effects of word frequency (e.g., Chee, Hon, Caplan, Lee, & Goh, 2002; Embick et al., 2001) and other lexical variables from being confounded with the effect of phonological

repetition. The remaining 240 words were filler items. Each filler item was always followed by a phonologically unrelated word. This was to minimize the predictability of where in the presentation sequence the phonological repetition would occur. Half of the filler items had homophones in the Japanese language; they were chosen to add to the complexity of the stimuli and helped to decrease the probability of predicting phonological repetition.

An example of the stimulus presentation sequence is shown in Figure 1. The 480 stimulus words were presented one by one. They were ordered pseudorandomly so that a first word was immediately followed by its homophone. We made eight lists of stimuli with a different order and randomly assigned them to 15 subjects. The stimulus presentation was divided into 24 blocks of 20 trials each. In each block, 5 homophone pairs and 10 filler words were presented. The first two items of each block were always filler items. After the last trial of each block, a recognition memory test was performed.

## Procedure

The subject lay on a bed with the right side down in a magnetically shielded room. The room was darkened during the recording. The stimulus presentation was controlled by a computer (PC9801BS2, NEC, Japan), and the stimuli were projected onto a screen by a video projector (BARCO3100, BARCODATA, Belgium) set outside the shielded room. The luminance of the stimuli and its background were 230 and 2  $\text{cd/m}^2$ , respectively. The stimuli were presented for 600 msec with a visual angle of  $1.45^\circ \times 0.65^\circ$ . The intertrial interval varied randomly between 500 and 600 msec. A fixation point (a red dot) was projected at the location corresponding to the center of the stimulus word throughout the recording. To reduce onset responses from the primary visual cortex, a sequence of random dot patterns ( $1.45^\circ \times 0.65^\circ$ ), which changed every 16.7 msec, was presented over the fixation point during the intertrial intervals.

The subjects were asked to read each presented word silently. They were not required to make any overt responses. To make subjects pay attention to the stimuli, a recognition memory test was performed between the blocks. In this test, a test word was presented on the screen, and the subjects were asked to report verbally whether the test word appeared in the immediately preceding block or not. To avoid subjects using a shape-matching strategy for the test and to ensure phonological processing of the stimulus words, the test words were written in a different script (Katakana, a Japanese syllabic script) from that used for writing the stimulus words (Kanji; see Figure 1). Thus memorizing the visual form of the words would not be a useful strategy for the test, and the subjects were thereby

required to memorize the stimulus words phonologically. They were also instructed not to repeat in their mind the stimulus words for memorizing them. For 15 blocks, a word that appeared in the block was presented as the test word, and for nine blocks a word that did not appear in the block was presented. The experimenter gave the subjects verbal feedback telling them whether their answer was correct or not before starting the next block. If necessary, the subjects were allowed to take a rest every four blocks. They were given one block as practice before the recording. The stimuli used in the practice block were different from those used in the recording blocks.

## MEG Recording and Analysis

Magnetic responses were measured with dual 37-channel gradiometers (Magnes, Biomagnetic Technologies, U.S.A.). The gradiometers were placed over the left and right temporal sites. The magnetic responses were recorded with a 0.1- to 50-Hz band-pass filter and were recorded digitally from 200 msec before to 600 msec after the stimulus onset at a sampling rate of 520.8 Hz. The magnetic responses were selectively averaged according to stimulus type (first word and homophone). The mean value of the signals during the 200 msec before the stimulus onset was used as the baseline. Epochs with signal variations larger than 3.0 pT were excluded from the averaging. Vertical and horizontal electrooculograms (EOGs) were recorded simultaneously to monitor eye movements (band pass, 0.1–30 Hz). Epochs with signal variations of larger than 100  $\mu\text{V}$  in the EOG were also excluded from the averaging. The averaged responses included at least 88 (73%) of the 120 trials. No digital filter was applied to the averaged responses. After the averaging, the waveforms of each channel and the isomagnetic field map at each time point were visually checked. When responses in a certain channel showed a large drift or the influence of magnetic responses other than the main responses, that channel was excluded from further analysis. Rejections of noisy channels were rare. For all subjects, responses from at least 36 channels were used for the analyses.

The strength of the magnetic responses was measured with the *SD* of the recorded responses across 37 channels at each time point. A dipolar source below the sensor array produces magnetic fields with high spatial derivatives (the flux is directed outward on one side and inward on the other). The variation between recorded responses would be higher in proportion to the strength of source activity. The *SD* value across channels thus represents the strength of magnetic responses. Compared with the RMS value, which is an index frequently used in MEG studies (e.g., Pantev & Lutkenhoner, 2000), the *SD* is resistant to a general drift of the responses produced by a distant source, which often includes sources other than the cerebral cortex. This is because

distant sources produce relatively uniform fields; thus the variation among recorded channels is low. The *SD* is therefore a suitable index of magnetic strength, especially when late responses are analyzed.

### Source Analysis

In our previous studies (Sekiguchi et al., 2000, 2001), multiple parts of the brain were activated simultaneously during visual word recognition. Thus, we conducted a multidipole source analysis using a brain electromagnetic source analysis (BESA, version 2.1m) (Scherger, 1992). BESA has a spatio-temporal modeling approach. It decomposes the recorded responses into a number of discrete neuronal source activities overlapping in time and estimates the strength and timing of each source current. BESA calculates the locations and orientations of dipoles in a spherical head conductor model by an iterative least squares fit. The goodness of fit of the sources was expressed as a percentage of the residual variance (%RV) between the observed fields and the theoretical fields. Because BESA has an interactive interface and does not find a source/sources automatically, a single equivalent current dipole model (Sarvas, 1987) was fitted for each time point, and the estimated sources were used as hypothesized sources in BESA.

The locations of the estimated sources were described in a head-based coordinate system. The origin of this system was set at the midpoint between the left and right preauricular points. The positive *x*-axis extended from the origin through the nasion. The positive *z*-axis extended from the origin through the top of the head such that it was perpendicular to the plane formed by the nasion and the preauricular points. The positive *y*-axis extended from the origin through the left side of the head such that it was perpendicular to the *x*- and *z*-axes. The locations of the three reference points were registered with a 3-D digitizer before the recording. The estimated source locations were overlaid on the subject's MR images to identify their anatomical locations. They were confirmed to be on or near the fissural cortex because MEG mainly detects activity in the pyramidal cells of the fissural cortex. T1-weighted MR images were obtained using a GE 1.5-T system (slice thickness, 1.0 mm) and a Shimadzu Medical 1.5-T System (slice thickness, 1.5 mm). The same anatomical landmarks used to create the head-based coordinate system were visualized in the MR images by affixing to these points high-contrast liver oil capsules. The common MEG and MRI anatomical landmarks allowed easy transformation of the head-based coordinate system to the MRI.

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