J. Biomed. Eng. Res : 170-179, 2006

An Extensive Analysis of High-density Electroencephalogram during Semantic Decision of Visually Presented Words

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(Received July 11, 2006. Accepted August 5, 2006)

Abstract

The purpose of this study was to investigate the spatiotemporal cortical activation pattern and functional connectivity during visual perception of words. 61 channel recordings of electroencephalogram were obtained from 15 subjects while they were judging the meaning of Korean, English, and Chinese words with concrete meanings. We examined event-related potentials (ERP) and applied independent component analysis (ICA) to find and separate simultaneously activated neural sources. Spectral analysis was also performed to investigate the gamma-band activity (GBA, 30-50 Hz) which is known to reflect feature binding. Five significant ERP components were identified and left hemispheric dominance was observed for most sites. Meaningful differences of amplitudes and latencies among languages were observed. It seemed that familiaritywith each language and orthographic characteristics affected the characteristics of ERP components. ICA helped confirm several prominent sources corresponding to some ERP components. The results of spectral and time-frequency analyses showed distinct GBAs at prefrontal, frontal, and temporal sites. The GBAs at prefrontal and temporal sites were significantly correlated with the LPC amplitude and response time. The differences in spatiotemporal patterns of GBA among languages were not prominent compared to the inter-individual differences. The gamma-band coherence revealed short-range connectivity within frontal region and long-range connectivity between frontal, posterior, and temporal sites.

Key words : event-related potential (ERP), gamma-band activity, visual word perception, coherence, independent component analysis (ICA)

I. INTRODUCTION

Various cerebral processes are involved in the visual perception of words, and thus multiple cortical regions are activated in sequence. Numerous neuroimaging and electrophysiological studies have been reported on visual word perception [1-6]. The neuroimaging studies, most of which utilized functional magnetic resonance imaging(fMRI), were focused on finding spatial locations of the neural correlates of word perception. Due to the limitation in temporal resolution, the monitoring of sequential neuronal activation during word perception is not possible by imaging techniques and electrophysiological methods such as electroencephalogram (EEG) or magnetoencephalogram (MEG) should be adopted instead. Time-locked averaging is usually performed to obtain so-called event-related potential (ERP). Statistical analyses of the identified ERP components are performed subsequently.

The visual word perception demands a considerable amount of cognitive resources and integration of information from multiple functionally connected neuronal circuitries at various scales. Visual perception of words involves multiple cerebral processes such as the encoding of shapes of letters, conversion of the shapes into orthographic patterns, and lexical/semantic decision. The monitoring of association of the involved neuronal assemblies is essential as well as the location and sequential order of activation. The rhythmic oscillation of neuronal activities in 30-50 Hz (gamma-band) as a means to mediate the formation of neuronal assemblies that jointly represent cognitive status [7-10]. The gamma-band oscillation is supposed as an indication of a temporal structure for the association among the neurons within the neuronal assemblies, i.e. the increase in synchronization of local neuronal populations. It is reasonable to assume that the EEG waveforms during the word perception may show noteworthy increase in

This study was supported by a grant of the Korea Health 21 R&D Project, Ministry of Health & Welfare, Republic of Korea (Grant number: A050251), and the Maeji research fund of Yonsei University.

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the GBA since it is expected that a significant association among neurons is expected. Some previous studies reported the GBA increase during language processing [11-14]. By calculating coherence in gamma-band, it may be also possible to quantify the functional connection among neuronal assemblies over widely separated areas.

The aim of this study was to explore the difference and similarity among sequential brain activation patterns during visual perceptions of Korean, English, and Chinese words, and to find out spatial and temporal origin of the difference, using 61 channel recoding of ERP. A comparative study on visual perception of the words from these three languages provides a unique opportunity to investigate the effect of written form on the cortical information processing, since it is expected that the process of visual perception of words from these three languages may not be markedly different. We performed an extensive analysis of the EEG recorded during visual word perception using multiple analysis techniques since different aspect of neuronal information processing may be revealed by different methods. Along with conventional statistical analysis of the averaged ERP, we investigated tentative neural sources identified by using independent component analysis (ICA) [15-17]. We also examined the spectral change in gamma-band by power spectrum, time-frequency analysis, and coherence among brain regions. Finally, we observed the relationships between time and frequency domain features of the EEG and response time.

II. METHODS

A. Experimental Methods

The details on experimental methods are described elsewhere [18]. Fifteen native Korean speaking subjects (7 females and 8 males, mean age: 25.4 ± 2.13) participated in this experiment. They experienced more than 6 years' education on Chinese characters, and written English. The stimuli consisted of 100 Korean, English, and Chinese words (300 words in total) with predetermined concrete meanings. All the Korean and Chinese words were equivalent phonetically and semantically, and thus, the numbers of characters of Korean and Chinese words were same. Each word was presented for 1000 ms (black on white background), just after showing a fixation mark ('+') for 500 ms. Inter-stimulus interval was 1500 ms. Subjects were requested to judge the meaning of presented words and respond as quickly and accurately as possible using mouse click (right hand middle finger for "non-living", the index finger for "living" categories).

The 61 channel EEG signals and vertical EOG were recorded according to 10/10 systems [1]. A bandpass filter (0.03 to 100 Hz) and notch filter (60 Hz) were applied. Sampling rate was 500 samples/s. Before the main recording experiment, EEG under baseline condition was recorded for approximately 1 minute while the subjects were requested to relax and keep their eyes open.

B. Data Analysis Methods

ERP epochs (-100 ~ +1000 ms) were averaged separately for three conditions (Korea, English, and Chinese). Severely contaminated segments were excluded by visual inspection. Five distinct ERP components were identified based on global field potential (GFP) plot and scalp topographies. Individual concatenated single-trial waveforms were decomposed by infomax ICA, using EEGLAB toolbox. [17]. The ICA was performed on 62 channel data (including 1 EOG channel) containing 280 ~ 300 single trials. The learning rate was kept lower than 10^{-8}. Meaningful independent components (ICs) from each subject were found and categorized by visual inspection of scalp topographies, time courses, activity power spectra, and amplitudes of single-trials sorted by stimulus onset.

The gamma-band power index (GPI) was calculated as the ratio between the power within 30-50 Hz band and the total power, at selected 12 electrode sites (Fp1, Fp2, F3, F4, C3, C4, P3, P4, T7, T8, O1, O2). Further details on spectral and time-frequency analysis are described in detail in [19]. Gamma-band coherence was obtained by the cross-power spectral density normalized by the auto-spectral densities, integrated in gamma range. The gamma-band coherence was calculated for 66 electrode pairs which were combinations of the selected 12 electrodes for every single trial. Statistical comparisons using analysis of variance (ANOVA) or t-test were performed among stimulus conditions (baseline condition vs. Korean/English/Chinese).

III. RESULTS

A. Time Domain Analysis of ERP

The average response times (RTs) for each condition (Korean, English, and Chinese) were statistically compared by repeated measures ANOVA. Average response time for Korean (672±23 ms) was the shortest, longer for English (782±28 ms), and the longest for Chinese (885±33ms) ($F(2,42)= 3.544$, $p=0.047$). The difference in RTs between Korean and Chinese was statistically significant (post-hoc test using Tukey's HSD, $p< 0.05$).

The averaged ERP waveforms are shown elsewhere [18]. Five significant components (or peaks) identified were P1

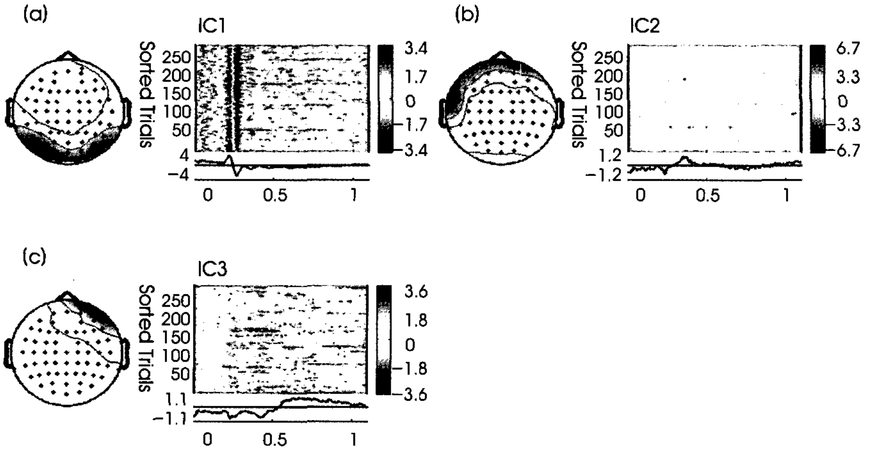

Fig. 1. Main independent components (Subject 7) (a) IC#1 (b) IC#2 (c) IC#3.

(104-124ms), N1 (160-180ms), N2 (250-280ms), P2 (280-310ms), LPC (500-700ms). The first component, P1, was characterized by a large bilateral positivity over posterior sites, and occurred approximately at 110 ms poststimulus at O1 and O2. No statistically meaningful interhemispheric difference was found for all languages ($p>0.54$). We also observed that the P1 amplitudes were not considerably modulated according to the written form of words ($F(2,42)=0.391$, $p=0.676$).

The second component, N1, was observed as prominent negativities at occipital and temporal regions, and analyzed at O1 and O2. Significant left lateralization was detected for

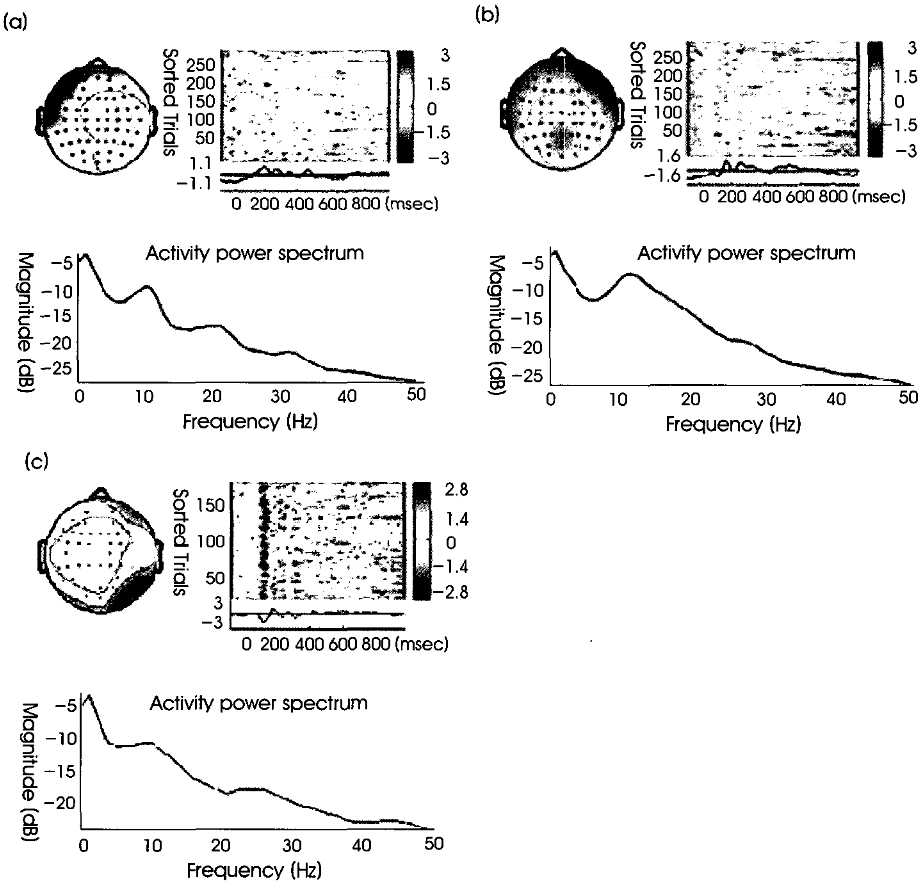

Fig. 2. Mu rhythm independent components (a) (a) IC#4 (b) IC#5 (c) IC#6.

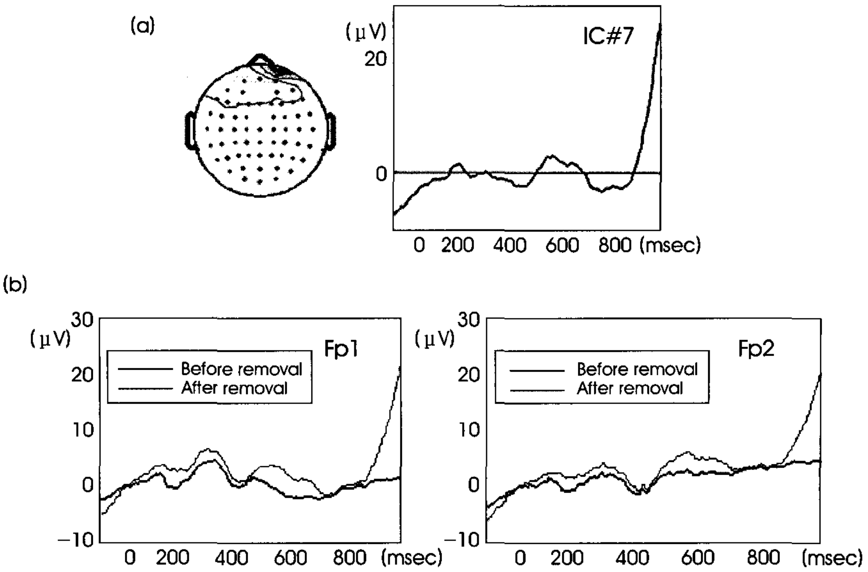

Fig. 3. EOG independent components (Subject 11) (a) IC#7 (b) ERP waveforms before and after removal IC#7.

Korean (t=2.199, p=0.028) and English (t=2.032, p=0.042). For Chinese, the N1 amplitude was larger for the left electrode, but it did not reach statistical significance (t=0.749, p=0.45). The N1 amplitudes were significantly dependent on the language (F(2,42)=6.168, p=0.02), and the order of the N1 amplitude was English>Chinese>Korean. The N2 component was most prominent at temporal sites and analyzed at TP9 and TP10. It was strongly modulated by the written form of language (Korean>English>Chinese, F(2,42)=67.098, p<0.000).

The P2 was identified as left lateralized positivity at frontal sites (Fp1 and Fp2). Its amplitude was not significantly dependent on language (Chinese>Korean>English, F(2,42)= 2.122, p=0.120). The activation of the frontal region was shifted toward right sites and right dominant positivity became prominent at later stage of sequential processing. The amplitude of this late positive component (LPC) was calculated as average between 500 700 ms at Fp1 and Fp2. It showed strong right lateralization (p<0.005 for three languages) and dependence on language (Chinese>English>Korean, F(2,42)=29.998, p<0.000).

The correlation between the amplitudes of each component and response times was observed. Generally, the late components that are expected to reflect frontal activity were highly correlated with the response time. The LPC amplitude showed highest correlation coefficients and strong statistical significance for all three languages (Korean: r=0.2803, p<0.0000; English: r=0.1161, p<0.0001; Chinese: r=0.4113, p<0.0000). The P2 amplitude was relatively highly and significantly correlated with the response time for Korean (r=0.1500, p<0.0000) and Chinese (r=0.3978, p <0.0000).

The decomposition of single-trials by ICA allowed identification and segregation of some ICs which seemed to be originated from the major regions involved in visual word perception. Rhythmic oscillatory activity and artifacts such as EOG and EMG were also observed. Fig. 1 shows the topographies and time courses of several ICs selected from 62 ICs derived from 300 trials of a subject (#7). The other components were ignored as their origins were not clear from their scalp topographies and IC waveforms, or were identified as artifacts. The IC#1 was identified as the early bilateral visual response at posterior scalp sites, which seems to correspond to the P1 and N1 ERP components. The IC#2 was the left lateralized positivity at prefrontal sites between 250 350 ms and thus roughly corresponds to the P2 component. The IC#3 was identified as the activation of the prefrontal region shifted toward right hemisphere and was prominent after 500 ms. Hence it may correspond to the LPC. These three ICs were observed in more than half of the subjects. The numbers of subjects that clearly showed these 3 ICs were as follows. IC#1: 11 (78.5 %), IC#2: 9 (64.29 %), IC#3: 10 (71.4 %).

An oscillatory activity was also identified by the ICA. Fig. 2 shows oscillatory components near 10 Hz which were reduced at or just before the response time (~500 ms). It is judged that this oscillatory activity corresponds to the mu rhythm [15] as it was recognized with the scalp topography, time course and power spectrum. The ICs identified as mu rhythms were categorized into three classes according the topography (left-central: IC#4, middle-central: IC#5, and right-central component: IC#6).

We also confirmed that some EOG and EMG artifacts could be found from ICA as several single independent components,

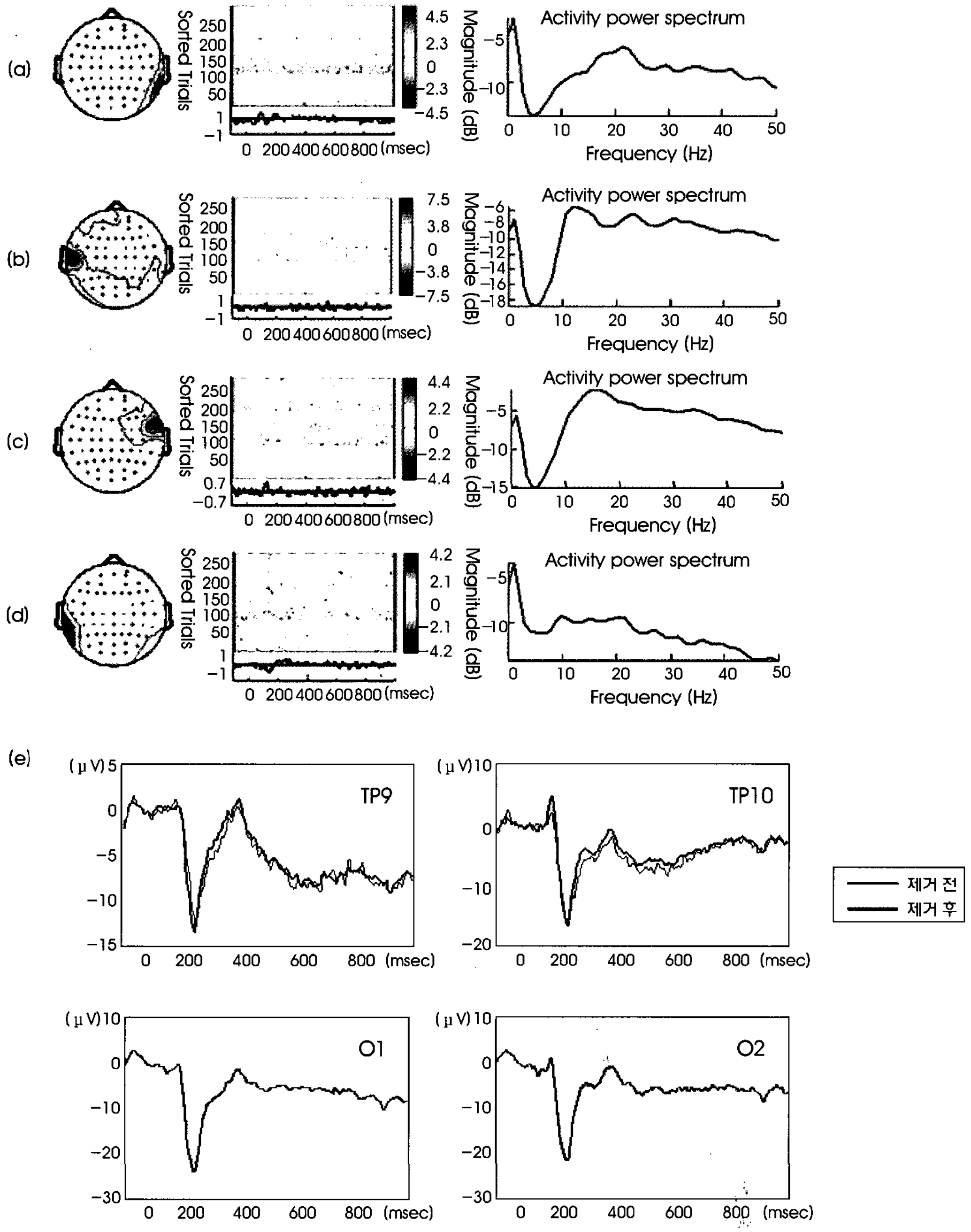

Fig. 4. EMG independent components (Subject 11) (a) IC#8 (b) IC#9 (c) IC#10 (d) IC#11 (e) ERP waveforms before and after removal IC#8 IC#11.

and could be successfully removed. Fig. 3 shows an IC (IC#7) that was identified as EOG artifact (Fig. 3 (a)), and ERP waveforms at Fp1 and Fp2 before and after the removal of IC#7 (Fig. 3 (b)). This IC was observed predominantly at periocular areas. Fig. 4 shows IC#8-IC#11 which were identified as temporal EMG artifact components and ERP waveforms at TP9, TP10, O1, O2 before and after the removal of these ICs. These EMG artifact components were regarded as temporal muscle activity, according to scalp topography (leftmost columns of Fig. 4 (a)-(d)), and power spectrum which shows high frequency components (the rightmost columns of Fig. 4 (a)-(d)). It was clear that single-trial ERP waveforms at temporal sites were contaminated by high frequency EMG-like activity (middle columns of Fig. 4 (a)-(d)). After eliminating the IC#8 - IC#11, the average ERP waveforms at TP9 and TP10 became free from the high frequency artifacts (Fig. 4 (e)). However, the ERP waveforms at O1 and O2 were not changed after the IC removal (Fig. 4

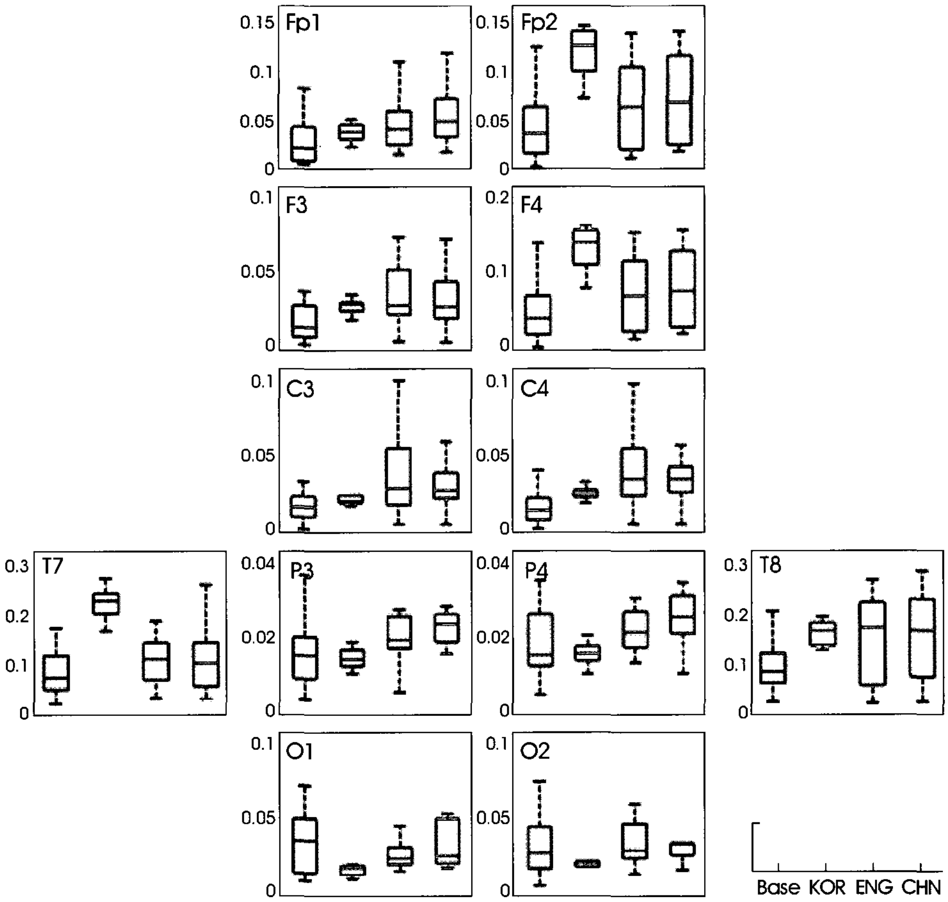

Fig. 5. The spatial pattern of GPIs (group).

(e)). The ICs IC#7-IC#11, which are judged to be originated from the temporal muscle EMG and EOG, were found from all subjects.

B. Gamma-band Activity

The spatial pattern of GPI averaged over all 14 subjects (group analysis) showed global increase of the GBA (Fig. 5). The tendency of prominent increases at prefrontal, frontal, and temporal sites was observed. Statistical significance was observed at all electrodes except O1. The numbers of subjects that showed statistically significant increases in individual analysis are as follows: Fp1- 10 (71.4 %), Fp2- 9 (64.29 %), F3- 9 (64.29 %), F4- 10 (71.4 %), C3- 6 (42.9 %), C4- 8 (57.1 %), T7- 10 (71.4 %), T8- 10 (71.4 %), P3 - 3 (21.4 %), P4- 5 (35.7 %), O1- 3 (21.4 %), O2- 5 (35.7%).

Comparisons between baseline and each language were performed by three separate paired t-tests and repeated-measures ANOVA. Similar results were obtained in that the prominent increase in GBA was observed at the prefrontal, frontal, and temporal sites. From the results of ANOVA (factor: language), we could verify significant increases during word stimulation, and differences of GPI among languages at nearly all electrode sites for all subjects. However, the dependences of GPI on language at different electrodes did not show any recognizable order with respect to languages. This disorder was observed both for the group analysis and individual analyses.

In order to investigate the lateralization of GBA, we performed pairwise comparison of the GPIs at left and right electrodes at prefrontal, frontal, central, temporal, parietal, and occipital sites by paired t-test. Right-hemisphere dominance was observed for most locations in most subjects. The numbers of subjects that showed statistically significant right-hemisphere dominance ($p<0.05$) are as follows: Fp- 12 (85.7 %), F- 13 (92.9 %), C- 11 (78.6 %), T (64.3 %), P- 7 (50 %), O- 10 (71.4 %). In group analysis, the right-hemisphere dominance was observed at all locations.

From the time-frequency distribution averaged over multiple subjects (figure shown in [19]), we could observe that the GBA increase occurred mainly during 150 ~ 500 ms interval. Global increase in GBA was observed. This is different from the case of ERP components where sequential

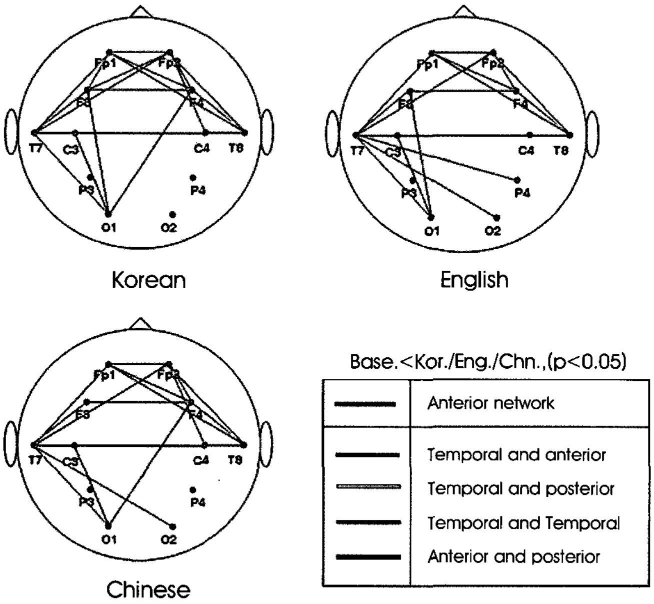

Fig. 6. Connections of the electrode pairs which showed significant increases in gamma-band coherence during stimulus condition ($p<0.05$).

activation of different regions is observed. Although the time-frequency distribution did not reveal any consistency over multiple subjects, we can observe prominent increases in GBA most noticeably at prefrontal, frontal, and temporal sites. The difference in time-frequency patterns of GBA across different languages was smaller compared to the inter-subject difference. We examined correlation coefficients between GPIs and the response times in order to find the location that shows significant correlation between GBA and behavioral performance. The GPIs at the prefrontal and temporal sites (Fp1, Fp2, T7, T8) were most highly ($|r|>0.15$) and significantly ($p<0.0001$) correlated with the response time.

C. Gamma-band Coherence

The coherence analysis was applied to reveal the functional connectivity in gamma-band during visual word perception. Fig. 6 shows the connections of the electrode pairs which showed significant increases in gamma-band coherence during stimulus condition compared to the baseline condition ($p<0.05$). The increase in gamma-band coherence within short-range network was observed at frontal areas. Significant coherence increases within the frontal area were observed between Fp1-Fp2, F3-F4, and Fp1-F4. Additionally, for Korean, it was also found between Fp1-F3 and Fp2-F3. The increase of long-range connection was observed between temporal and frontal areas, between left temporal and posterior areas, between the left and right temporal areas, and between frontal and left occipital areas. It is shown in Fig. 6 that the frontal sites (Fp2, F3, and F4) were strongly connected to left and right temporal regions (T7 and T8) for all three languages. The increase in coherence between left temporal and posterior areas was observed for both English and Chinese (T7-O1 and T7-O2, respectively).

The increase in coherence between frontal and left occipital areas was found between C3-O1 for all three languages. For Korean and English, it was also observed between F3-O1, and for Chinese, between F4-O1. The increase in coherence between T7-T8 was observed for all three languages. The mean coherence above 0.5 was achieved within frontal areas, i.e., between Fp1-Fp2, Fp1-F3, Fp1-F4, and Fp2-F4.

Ⅳ. DISCUSSION

The observed order of response time (Korean<English <Chinese) was as expected. Post-hoc t-test showed statistically significant difference in the response time between Korean and Chinese only. These results are consistent with the expected relative familiarity with English words of Korean subjects compared to written Chinese words. The significant correlation between the response time and the P2/LPC amplitude appears to be reasonable because these later ERP components with frontal origins are more closely related to the semantic decision.

The early visual component, P1, showed strong bilateral activation and no dependence on language. The P1 amplitude was not modulated by the written form of words in our experiment, where the stimuli consist of words only. This may reflect the fact that the activity of P1 (P100) may be originated from very early stage of the central visual pathway [20] so that the dependence on the category of stimulus hardly appears during this epoch. The N1 amplitude was the largest for English, then Korean, and the smallest for Chinese. It is well known that the processing of alphabetic language in this epoch shows left-hemisphere dominance [21,22,23]. It is assumed that this area plays an important role in early visual perception of language because it does not only carry the information from primary visual area passively, but actively contributes to visual form processing and triggers the retrieval of the meaning, grammatical features, and pronunciation [24].

By 250 ~ 280 ms, the activity of occipital and temporal region was shifted to more lateral and anterior regions, and the bilateral negativity, N2 was observed. The amplitude of the N2 was modulated according to the relative familiarity with each language (Korean>English>Chinese). Activation covered a broad range of occipitotemporal cortices and showed the temporal organization of enhanced visual area activity in response after stimulus onset at about 250 ms. At the epoch of N2, left-dominant positivity at frontal region, P2, was concurrently observed. The P2 seems to reflect semantic processing and early stage of decision. Some previous studies supports this idea and argued that this time epoch is devoted to semantic processing, and the coexistence of frontal and posterior activities at this epoch [5,23]. The latest ERP component, LPC, was the right-hemisphere dominant positivity at frontal region. The LPC amplitudes were similar for Chinese and English and smaller for Korean. Considering that the LPC may reflect reconstruction, recollective process, and more detailed processing of input based on long-term memory [25], relatively small response for Korean, which is more familiar for the subjects, seems to be reasonable. Our observation of the sequential pattern of frontal activity is similar to that of Liu and Perfetti [26], i.e., 'left-then-right'.

From the results of ICA, it was possible to confirm that some of the ERP components correspond to the spatially fixed and temporally independent activities. The most prominent IC seems to reflect the early visual responses at bilateral posterior sites corresponding to the P1 and N1 components of the averaged ERP. We could also find two ICs that seems to correspond to the P2 and LPC respectively. However, these results were obtained from the individual analysis and it was not possible to extract some distinct ICs from group analysis. Further study is necessary to confirm the efficacy of the ICA in identifying the independence of each ERP component. A task should be designed so that inter-individual difference is minimized.

Rhythmic oscillation components which were unobservable by averaged ERP could be observed by the ICA. Activation of these components had spectral peaks at alpha band and their waveforms were reduced at about 280 ms earlier than the response time. These components were known as mu rhythm, and were predominant at central sites, corresponding to the motor and somatosensory cortices, as shown by MEG experiment and source localization [30]. It was judged that the mu rhythm reflects the desynchronization of motor cortical neurons during the preparation of movements. ICA was also very effective in recognizing and eliminating the EOG and EMG artifacts.

The results of spectral analyses showed global increase with right-hemisphere-dominance for all three languages. The increases in GBA were most prominent at prefrontal, frontal, and temporal sites, and these appear to be coincident with major cortical areas involved in visual word perception. The GBAs at prefrontal and temporal areas were significantly correlated with the response time. The differences in spatiotemporal patterns of GBA among languages were not considerable compared to the inter-individual differences.

The areas of prominent GBA increase, i.e. prefrontal, frontal, and temporal regions, are known to play important roles in visual word perception [10,22,27,28]. It appears to be reasonable that a large amount of association among neurons and/or neuronal assemblies was produced in those regions where the neural substrates of underlying task are located. It is also in line with a recent result that showed strong correlation between hemodynamic signal and gamma-band oscillation [29]. The coincidence of the spatial locations of high GBA and the putative sources of neuronal activities is in line with the study of Fitzgibbon et al. [31], where it is reported that the site of prominent GBA increase is changed according to the given task.

The difference in spatial and temporal pattern of GBA with respect to language was smaller than the inter-individual difference. This is comparable to a previous study which reported that the amount and location of GBA increase under cognitive tasks is significantly different for each subject [31]. From these results, it is judged that the inter-individual difference in the temporal structures for information integration at specific cortical region is substantial. This is in contrast to the fact that the location of sources and their sequential order of activation may be common across multiple subjects, which is the basis for the group analysis of ERP and neuroimaging studies. Prominent GBA increases were observed over a wide range of 150 500 ms interval after stimulus onset [10] for the duration of reading task.

Contrarily to the conventional assumption of the left-hemisphere dominance in language processing, a significant involvement of the right-hemisphere was revealed by both the ERP and spectral analysis. This was also reported by many preceding studies on word perception. MacLeod et al. [32] reported the activation of right frontal region during semantic word processing/working memory task. Fu et al. [3] reported that bilateral frontal region was activated in word reading task which did not explicitly evoke semantic decision. Tan et al. [33] judged that relatively strong activation of right frontal region in Chinese word reading is relevant to the demand of intense fine-grained analysis of spatial features. The right frontal activation was also attributed to the allocation of attention resources and visuospatial analysis of information [34]. It seems to be difficult to judge the exact role of the right frontal region from these previous studies, since there are large amount of variation in involved tasks. The sequence of frontal activation found in this paper may help clarify the role of right frontal region in semantic word processing. For example, it may be inferred that at first, semantic/phonological processing is performed by the left frontal region and subsequently, the right frontal region is activated for more careful analysis of spatial features. Obviously, further study is required to elucidate the function of sequential activation of frontal cortex.

Gamma-band coherence increased globally for all three languages. Strong short-range connection was significant within frontal area and the increase in long-range connection was observed between temporal and frontal areas, between left temporal and posterior areas, between frontal and left occipital areas, and between left and right temporal areas. These regions overlapped the tentative spatial locations of significant ERP components and the high GBA. Synchronization in gamma-band have been assumed to perform the role of assembling a broadly distributed set of neurons during a cognitive act [35,36] so that functional and temporal structure among brain regions for integrated information processing is revealed [37]. Strong short-range gamma-band connection within frontal region may be correlated with increased demand on working memory [38]. Large-scale neuronal synchronization may be important for the distributed neuronal assemblies to be integrated so that large-scale cognitive integration is formed [36,39]. Previously, the fronto-parietal coupling in gamma-band was observed in the left hemisphere during the encoding condition and in the right hemisphere during the retrieval condition [40].

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