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Neuromagnetic correlates of hemispheric specialization for face and word recognition

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ABSTRACT

The adult human brain appears to have specialized and independent neural systems for the visual processing of faces and words: greater selectivity for faces in the right hemisphere (RH) while greater selectivity for words in the left hemisphere (LH). Nevertheless, the nature of functional differences between the hemispheres is still largely unknown. To elucidate the hemispheric specialization for face and word recognition, event-related magnetic fields (ERFs) were recorded in young adults while they passively viewed faces and words presented either in the right visual field or in the left visual field. If the neural correlates of face recognition and word recognition reflect the same lateralization profile, then the lateralization of the magnetic source of the M170 component should follow a similar profile, with a greater M170 response for faces in the RH and a greater M170 response for words in the LH. We observed the expected finding of a larger M170 in the LH for words. Unexpectedly, a larger M170 response in the RH for faces was not found. Thus, the hemispheric organization of face recognition is different from that of word recognition in terms of specificity.

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1. Introduction

Hemispheric specialization is an important feature of cortical function in humans. The recognition of faces and visual words is a central skill required for social communication in everyday life. Consequently, the human brain has special and specific neural circuits to identify faces and visual words. Several lines of evidence suggest that the face recognition circuit shows greater selectivity to the right hemisphere (RH) than the left hemisphere (LH), while the circuit for word recognition shows greater selectivity to the left than the right hemisphere (Behrmann and Plaut, 2013; Cohen and Dehaene, 2004). The key issue addressed by the current work concerns the profile of lateralization for face and word recognition using magnetoencephalography (MEG).

Behavioral, neuropsychological, and neurophysiological studies have suggested that face recognition is processed by independent neural systems distinct from those for the recognition of other categories of visual stimuli (Wada and Yamamoto, 2001; Puce et al., 1999). This face-selective network includes the core regions in the ventral surface of the occipital and temporal lobes, such as the occipital face area (OFA) (Gauthier et al., 2000), the fusiform face area (FFA) (Kanwisher et al., 1997), and the posterior region of the superior temporal sulcus (STS) (Puce et al., 1998; Haxby et al., 2000). The OFA and FFA are both involved in identifying facial invariant features (Weibert et al., 2018). Electrophysiological studies have indicated that the event-related potential (ERP) of the N170 component reflects the activity of the encoding stage of face structure (Bentin et al., 1996), and a greater N170 is consistently found in the right occipital cortex (Scott and Nelson, 2006). Accordingly, acquired prosopagnosia may occur in bilateral or right-sided lesions of the occipital or temporal lobes (Gainotti and Marra, 2011).

Abbreviations: ANOVA, analysis of variance; CVF, central visual field; dSPM, dynamic statistical parametric mapping; ERF, event-related magnetic field; ERP, event-related potential; FA, fusiform gyrus area; FFA, fusiform face area; HPI, head position indicators; LH, left hemisphere; LVF, left visual field; MEG, magnetoencephalography; MNE, minimum-norm estimate; MRI, magnetic resonance imaging; OA, inferior occipital area; OFA, occipital face area; RH, right hemisphere; ROI, regions of interest; RSS, root-sum-square; RVF, right visual field; SOI, sensors of interest; STS, superior temporal sulcus; VWFA, visual word form area.

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Moreover, Rangarajan et al. (2014) observed a striking difference between the two hemispheres: Only electrical stimulation of the right FFA caused distortions of faces, while electrical stimulation of the left FFA produced non-face related visual changes, such as phosphenes.

The LH predominance over the RH for visual word processing is well acknowledged in right-handed adults. Thus, a large number of neuroimaging studies report that the LH plays a major role in reading. The network for visual words includes a specific region of the left ventral occipito-temporal cortex. This has been labeled the visual word form area (VWFA) (Cohen et al., 2000) and responds more to visual words than to any other category of stimuli. One split-brain study has clearly shown a right visual field bias for words (Sperry, 1982). ERP studies consistently show greater N170 potentials for words in the left occipital cortex than right one (Maurer et al., 2008; Mercure et al., 2011). Thus, it is generally accepted that the left VWFA is involved in reading and that learning to read increases activity in this area (Dehaene et al., 2010).

It is the common anticipation that the ability of visual word recognition and that of face recognition were independent of each other. Face recognition is most likely an essential ability in being able to communicate, and in human beings, it is acquired early after birth. In contrast, reading tends to be acquired by education several years later. Furthermore, the evolutionary status of words and faces are fundamentally different: reading is a relatively recent invention, introduced several thousand years ago (Dehaene and Cohen, 2007). This evolutionary time course is obviously not the case for face recognition. However, some researchers have theorized that the functional lateralization of face processing has occurred as a consequence of language development in humans (Allison et al., 1994; Dehaene et al., 2010; Dundas et al., 2014), which shows strong left lateralization. These findings suggest that the neural mechanisms for face and word recognition did not develop independently and that earlier LH word lateralization has driven later RH face lateralization.

Information relating to right visual field stimuli is initially perceived by the left visual cortex. This process relies exclusively on the pathways confined to the LH and vice versa. In this study, the M170 component (a counterpart of the N170 component of ERPs) was used to assess hemispheric specialization. If the neural correlates of face recognition and word recognition reflect the same lateralization profile (Behrmann and Plaut, 2013; Cohen and Dehaene, 2004), then the lateralization component should follow a similar profile, that is, a greater M170 response or a shorter M170 latency for faces in the RH and a greater M170 or a shorter M170 latency for words in the LH. Therefore, the first objective of this study was to examine differences between the hemispheres during the processing of faces or visual words using hemi-field stimulation (right visual field (RVF) vs. left visual field (LVF)). Two key brain structures implicated in the recognition of both faces and written words are the FFA (Kanwisher et al., 1997) and the VWFA (Cohen et al., 2000). Our second objective was to determine how these face- and word-selective regions may interact with each other. Here, neuromagnetic data are presented that support a new view proposing that processes relating to hemispheric category-selectivity for face and word recognition are influenced by one another.

2. Materials and methods

2.1. Participants

Nineteen healthy adults (10 females, aged 20–45 years old (mean 28.6 ± 8.7 years)) participated in both the face and visual word experiments. They had normal or corrected-to-normal vision and no history of reading difficulties or neurological diseases. All participants were native Japanese speakers. Their handedness was assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). After being given a complete description of the study, all participants gave written informed consent. Ethical approval was provided by the Ethics Committee of the Graduate School of Medical Sciences, Kyushu University.

2.2. Visual stimuli

There were two stimulus conditions: faces and words. Fig. 1 shows examples of the stimuli used in this study. All image processing was conducted using MATLAB ver. 7.5 (The MathWorks Inc., Natick, MA). Face and word stimuli were processed with Matlab 7.5 to equalize contrast, brightness, and average luminance. The luminance of stimuli was 76.8 cd/m^2 while that of the background was 39.0 cd/m^2.

2.3. Face stimuli

The stimuli consisted of three types of gray-scale photographs: fearful faces, neutral faces, and objects (287 × 367 pixels). Face images were obtained from the ATR database (ATR Promotions, Inc., Kyoto, Japan). Eight identities (four males, four females) were used to convey fear and neutral facial expressions from a frontal view. Face stimuli were cropped into an oval shape so that external features (e.g., hair and face contour) were removed. We used object stimuli as a control, and selected eight commonly used objects (coin, cap, shoes, etc.). As this current study focusses on the differences between face and word networks, the fearful faces were not analyzed.

2.4. Word stimuli

The Japanese writing system is composed of a complicated combination of ideograms (Kanji) and phonograms (Kana). Kanji is a logographic writing system using characters that directly correspond to words. Like the alphabet, Kana is a syllabic writing system that involves direct phonetic reading. Thus, we used three types of stimuli; Kana, Kanji, and scrambled word stimuli (174 × 367 pixels). Stimuli were presented in black Gothic font against a gray background. Eight Kanji stimuli were selected from meaningful words learnt in the lower grades of elementary school, and were represented by two Kanji ideograms that could be phonetically transcribed as three Kana letters. In the word condition, scrambled stimuli was used as a control. To create the scrambled stimuli, we gridded the four Kanji and four Kana word into twelve (Kana) or eight (Kanji) square sections and shuffled them at each position. Overall, eight each stimulus, a total of 24 images were used. In this study, we adopted Kana to explore the word reading system because Kana is much easier to read and evoked a much larger N170 response compared with that of Kanji in our previous study (Horie et al., 2012).

2.5. Procedures and task

Participants participated in two experiments, one for faces and one for words, on separate days. The order of the experiments was counterbalanced across participants. They were seated in an upright position approximately 140 cm from the monitor inside a magnetically shielded room. All experiments were conducted using PsychoPy (Peirce, 2007, 2008) and presented on a 19-inch liquid crystal display (CG-L19 DSWV2; Corega Inc., Japan).

For each experiment, there were 1080 trials, which were split into six blocks to allow participants time to rest in between blocks. Each trial comprised a central black fixation for 1200 ms and red fixation for 800 ms (Fig. 1c). At the same time, visual stimuli were

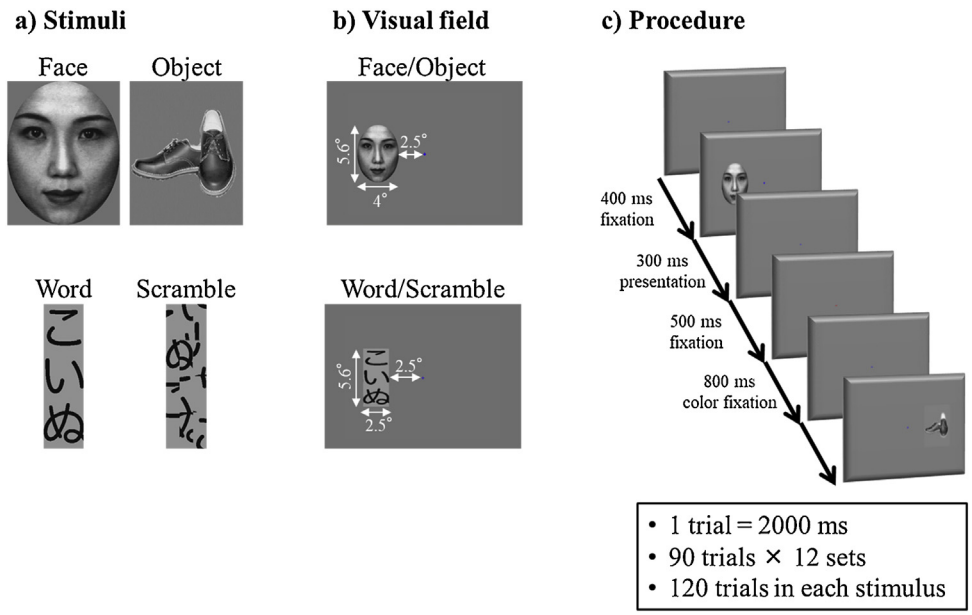

Fig. 1. a) Examples of the visual stimuli used in this study: images of a human face and object (upper row) and Japanese words (Kana) and scrambled words (lower row). b) Visual stimuli were presented in each visual field. In this example, visual stimuli were presented in the left visual field. For comparison, the visual stimuli were also presented in the central and right visual fields. c) Each stimulus (face, object, word, or scrambled word) was presented for 300 ms. Then the central fixation point (black or red) was presented throughout the trial.

presented from 300 ms to 700 ms after the onset of stimuli. The visual stimuli appeared in the central visual field (CVF), LVF and RVF, respectively. The location of the visual field was randomized for each participant, with equiprobable presentation of stimuli in each field within a block. The visual angles for the left or right visual field stimuli were 5.6° vertically and 2.6° horizontally. In total, the entire experimental session lasted approximately 45 min. CVF stimulation was performed to ascertain that the face and word stimuli evoked a clear M170. The M170 responses to the CVF were also used to infer the interhemispheric connectivity between the hemispheres.

The participants were instructed to keep their gaze at central fixation throughout the experiment to limit eye movements. The ERF data were recorded while participants passively viewed stimuli without any instructions. To focus participants' attention toward the visual stimulation, the task required them to respond as accurately and quickly as possible by pressing a button with the index finger of their left or right hand when the color of the fixation changed from black to red. Participants' left and right hands were used alternately during the recording block. All participants scored >94.5% on the fixation task averaged across all blocks.

2.6. Data acquisition

The MEG data were obtained with a whole-head-type 306-channel sensor array (Neuromag; Elekta Helsinki, Finland). Before recording, we attached four head position indicators (HPI) to the scalp of each participant. The HPI coil locations were measured along with three fiducial points (bilateral preauricular points and the nasion) and around 150 additional scalp locations using a 3D digitizer (Fastrak; Polhemus, Colchester, VT, USA). Prior to recording for each block, we performed head localization. MEG data were acquired with an online bandpass filter of 0.1–330 Hz and were continuously sampled at 2005 Hz. Participants maintained their initial head position throughout the recording. Their vigilance was carefully monitored by a video camera positioned in a shielded room.

We recorded structural magnetic resonance imaging (MRI) with a 3.0-T high resolution MRI scanner (Actieva 3.0 T TX, Philips electronics, Netherland). MRI images were used for MEG-MRI co-registration and subsequent source localization analysis.

2.7. Data analysis

2.7.1. Pre-processing

The all raw MEG data were processed using MaxFilter 2.2.15 software (Elekta Neuromag) to remove noise signals from outside using the signal source separation algorithm (Taulu and Simola, 2006). We applied a band-pass filter in the 1–40 Hz range as an off-line filter. Epochs were baseline-corrected using 100 ms pre-stimulus baseline and were rejected when the magnetic field variation at any planar-type gradiometer exceeded 4000 fT/cm before averaging. The artifact-free data were segmented from 100 ms before to 500 ms after the onset of stimuli.

Using FreeSurfer software (Dale et al., 1999; Fischl et al., 1999), we reconstructed the cortical surface image of each participant from their T1-weighted images. The extracted MRI contour image and the MEG head coordinate system using the scalp surface points obtained by the 3D digitizer were co-registered.

2.7.2. Analysis of event-related magnetic fields

For the sensor-based event-related magnetic field (ERF) analysis, at least 80 artifact-free magnetic responses were averaged in each stimulus. Next, we performed a root-sum-square (RSS) analysis of the averaged waveforms of each paired sensor. We then determined the sensors of interests (SOIs) for face and word perception. Fig. 2 shows schematic images of the SOIs in the representative data. We identified the strongest M170 paired sensor that showed the maximum RSS amplitude between 110 and 220 ms in the occipital-temporal region of each hemisphere. The eight paired sensors closest to the strongest sensor were selected, and a total of nine paired sensors were defined as the SOI. Finally, the RSS signals from these nine paired sensors were averaged to generate one virtual sensor. Here, we define the M170 as the maximum RSS amplitude in each SOI within 110–220 ms.

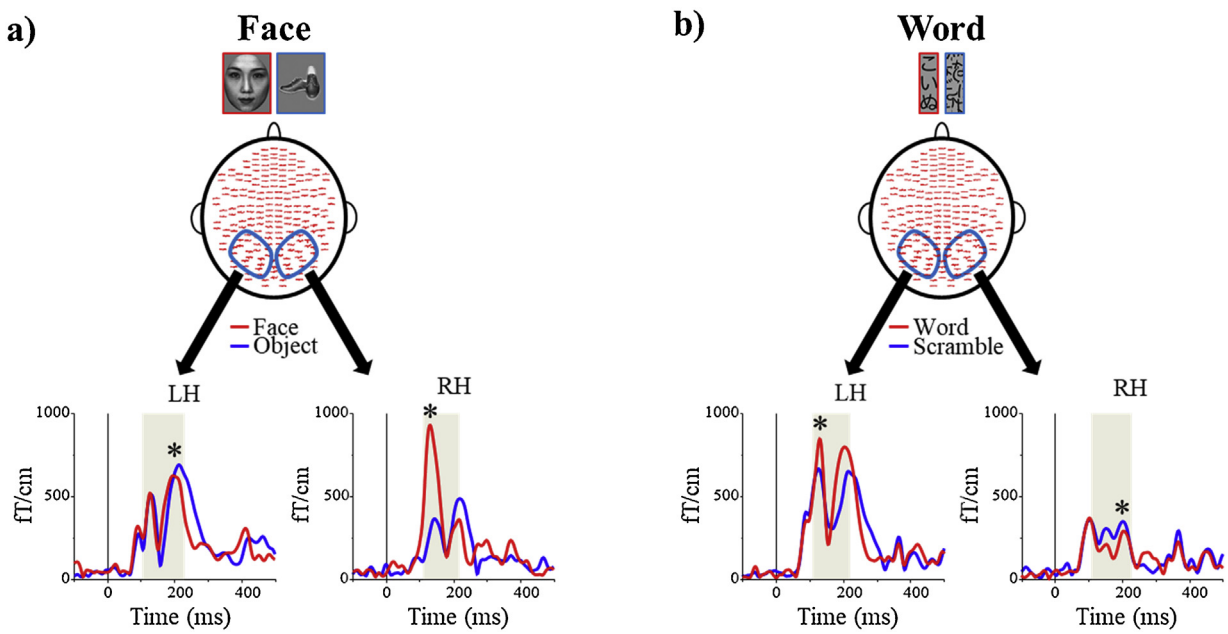

Fig. 2. Representative examples of the M170 waveforms (root-sum-square) in response to each visual stimulus in a representative participant for the sensor of interests (SOIs). SOIs consisted of nine paired sensors outlined by blue ellipses. a) In the face condition, a clear M170 appeared only for face stimuli (red line) predominantly in the right hemisphere (*). b) In the word condition, M170 appeared for word and scrambled stimuli mainly in the left hemisphere (*). The M170 for word (red line) was larger than that of scrambled kana (blue line). This Kana word means 'puppy'. Abbreviations: LH, left hemisphere; RH, right hemisphere in this and subsequent figures.

2.7.3. Source-level analysis

The focus of the study was on the analysis of source data relating to the M170 that was distinctive to faces or words. Early components at around 100 ms (M100) reflected responses in the primary visual cortex and were evoked by every visual stimulus. As we intended to examine the face- and word-selective cortical responses, we subtracted the waveforms as follows: face – object and word - scrambled word. By using these subtracted waveforms, we eliminated the M100 effects and isolated the regions responding more to either faces or words than to non-faces or non-words.

Source level analysis was performed to eliminate activities in multiple ventral and dorsal regions that overlap temporally and spatially. We used minimum-norm estimate (MNE) and dynamic statistical parametric mapping (dSPM) for source reconstruction analysis (Dale et al., 2000; Molins et al., 2008; Lin et al., 2006). The MNE and dSPM was performed based on our previous studies (Hayamizu et al., 2016; Kume et al., 2016). In brief, we calculated the noise covariance matrix from −100 to 0 ms in the pre-stimulus interval for noise-normalization. For the MNE analysis, we used the ERF averaged data for each condition.

Regions of interest (ROIs) were determined using a label file imported from brain annotation provided by FreeSurfer (aparc-a2009). The coordinates for the FFA, OFA, and VWFA reported previously in studies of face and word recognition were plotted on the standard brain. The FFA and VWFA were located in the fusiform gyrus area (FA), and the OFA overlapped into the inferior occipital area (OA). We defined these areas in each hemisphere as the ROIs, and four ROIs were selected for the source-level analysis (Fig. 3a).

These ROIs included many extra areas that were not related to face or word recognition and therefore, waveforms for further analyses were calculated. First, we estimated the waveforms of each vertex separately for each stimulus condition in the ROIs, and then created subtracted waveforms across all vertices ((face - object) or (word - scramble word)). Second, the largest amplitude between 110 and 220 ms post-stimulus was estimated for each subtracted waveform of the vertex. Third, final waveforms were calculated by averaging the subtracted waveforms containing the amplitudes of the top 10% of magnitudes (Fig. 3b).

We determined the latency and amplitude as the time and magnitude of the largest response between 110 and 220 ms for activity from the averaged waveforms. The waveforms were visually inspected and those with no obvious peak were excluded from latency analysis. We defined highest amplitude between 110 and 220 ms as amplitude of no peak waveforms.

2.8. Statistical analysis

All statistical analyses were performed using JMP (version 12.2.0, IBM Corp, Armonk, NY). In the CVF stimulus task, two-way repeated measures analysis of variance (ANOVA) was performed to determine differences between ROIs (FA, OA) and hemispheres (RH, LH). In the hemi-visual field task, three-way repeated measures ANOVA was performed to determine the effects of visual field (RVF, LVF), ROI (FA, OA) and hemisphere (RH, LH) on ERF responses. Post hoc analyses were conducted for multiple comparisons. P values less than 0.05 were considered to indicate statistical significance.

3. Results

3.1. Handedness

Of the total 19 participants, 17 were right-handed as determined by the Edinburgh Handedness Inventory (all with an index higher than 0.8, mean 0.96 ± 0.06). Two participants were not right-handed (both with an index lower than 0). Therefore, these two participants were excluded from further analysis, because left-handed participants are more likely to display atypical lateralization of both facial and visual word networks (Cai et al., 2008; Van der Haegen et al., 2012).

3.2. Visual recognition

After the experiment, we confirmed that all participants recognized all of the visual stimuli, even in the hemi-field stimulation condition.

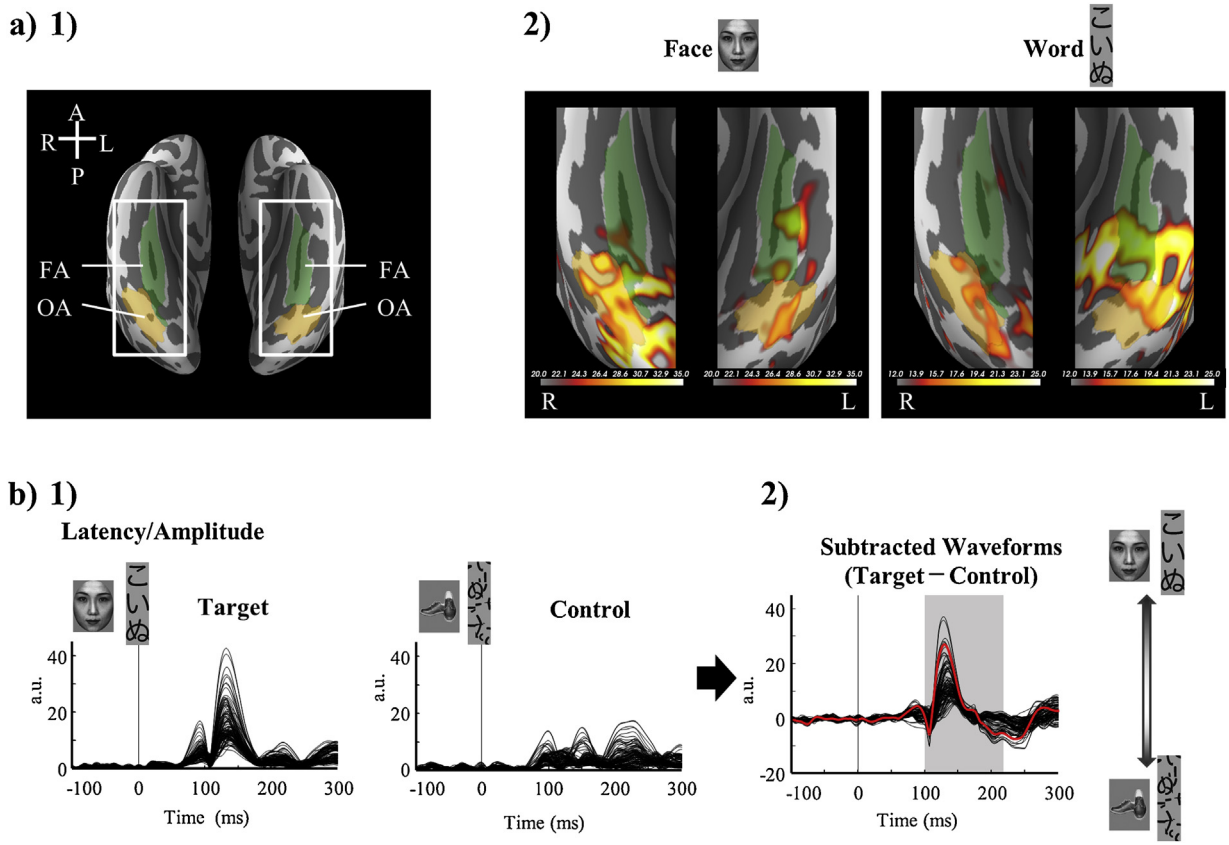

Fig. 3. Methodological procedures for the source level analysis (a). 1) ROIs were obtained from label annotation based on FreeSurfer software (inside the brackets shows original FreeSurfer annotation). FA; G_oc_temp_lat_fusifor (green), OA; G and S occipital-inf (orange). 2) ROIs for faces and words showing the dSPM results with activation patterns for each condition in the representative data. In the face condition, the bilateral OAs and FAs were clearly activated. In the word condition, the left OA and FA were activated. Face- and word-selective cortical responses (b). 1) Estimated waveforms of vertices in the ROI separately for each stimulus condition. 2) Subtract waveforms across all vertices (face-object or word-scrambled word) (black waveforms). Average subtracted waveforms containing the amplitude of the top 10% magnitude between the 110 and 220 ms post stimulus (red waveforms) are shown. Averaged waveforms were used to quantify the M170 response. The a.u. (arbitrary unit) in the ordinate denotes dSPM values. Abbreviations: ROI, region of interest; FA, the fusiform gyrus area; OA, the inferior occipital area; dSPM, dynamic statistical parametric mapping in this and subsequent figures.

Table 1
Results of the two-way repeated ANOVA for source data of the central visual field stimulation.

Factor	Latency		Log amplitude	
	F	p	F	p
Face				
ROI	1.89	0.18	0.0046	0.95
Hemisphere	0.25	0.62	4.19	**0.046**
ROI × hemisphere	0.082	0.78	0.079	0.78
Word				
ROI	0.38	0.54	0.74	0.39
Hemisphere	0.52	0.48	13.13	**0.0007**
ROI × hemisphere	0.068	0.80	0.081	0.78

ROI, OA/FA; Hemisphere, LH/RH.

3.3. Face experimental session

3.3.1. Effects of CVF stimulation

Fig. 4a shows the scatter plots with bar graphs of the latencies and amplitudes of the M170. Two-way ANOVA results for the M170 latency and amplitude are summarized in Table 1. With respect to the M170 latency, there was no significant main effect of ROI (FA and OA) or hemisphere. No significant interaction between ROI and hemisphere was found. Regarding the amplitude, there was a significant main effect of hemisphere but not ROI (Table 1). However, there was no significant interaction between ROI and hemisphere. A post hoc analysis confirmed that the amplitudes in the RH were significantly larger than those in the LH for the OA but not FA.

3.3.2. Effects of hemi-visual field stimulation

Fig. 5a shows the scatter plots with bar graphs of the latencies and amplitudes of M170. Three-way ANOVA results for the M170 latency and amplitude are summarized in Table 2. For the latency of the M170, there was no significant main effect. However, there was a significant interaction between visual field and hemisphere. A post hoc analysis confirmed that the latencies of the contralateral hemisphere were significantly shorter than those of the ipsilateral hemisphere in the OA and FA. With respect to amplitude, there was a marginal effect for ROI. There was a significant interaction between visual field and hemisphere. There was no significant difference between the hemispheres. A post hoc analysis showed that the amplitudes in the FA tended to be larger than those in the OA.

3.4. Word experimental session

3.4.1. Effects of CVF stimulation

With respect to the M170 latency, there was no significant main effect for ROI or hemisphere (Fig. 4b, Table 1). There was also no significant interaction between ROI and hemisphere. Regarding the amplitude, there was a significant main effect of hemisphere but

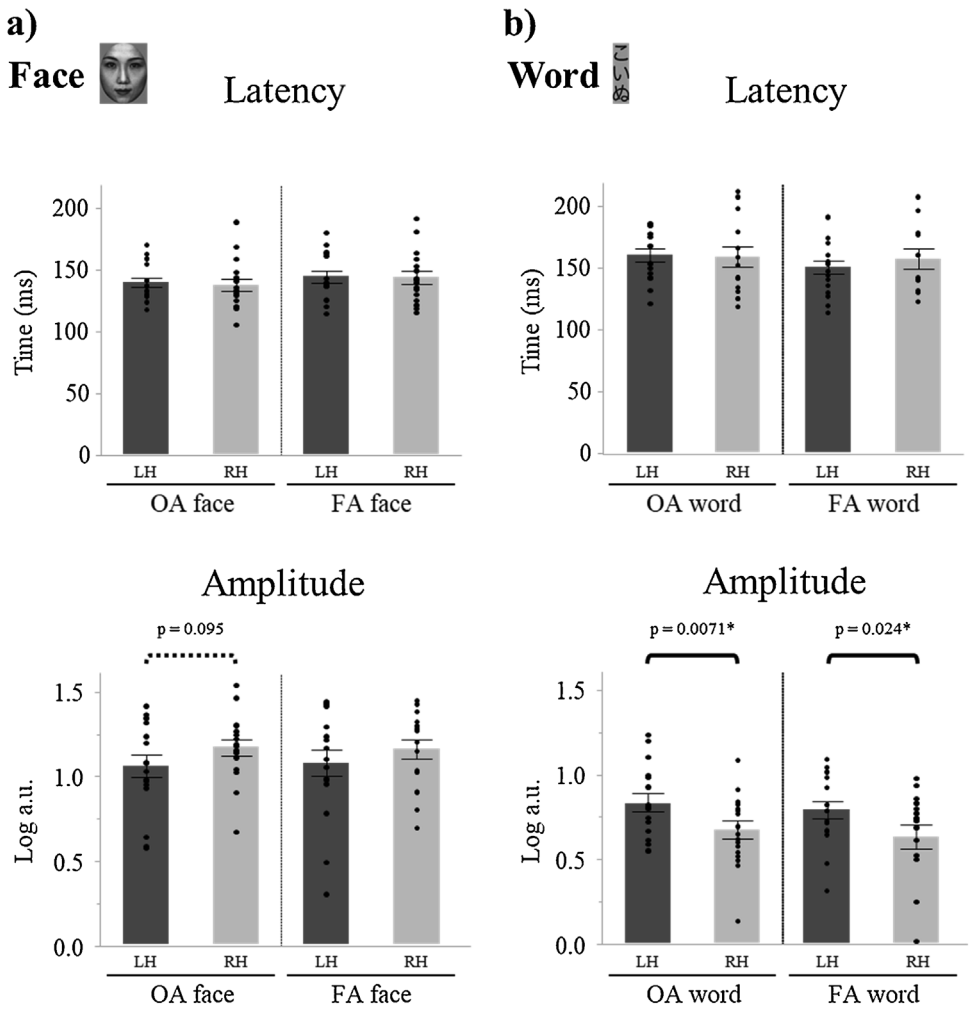

Fig. 4. Effects of the central visual field stimulation on the M170 responses to faces (a) and words (b). a) In the face condition, latencies were unaffected by the stimuli while the amplitudes in the right hemisphere were predominant for the OA but not the FA. b) In the word condition, latencies were unaffected by the stimuli. However, the amplitudes in the left hemisphere were predominant for both the OA and FA.

Table 2
Results of the three-way repeated measures ANOVA for the source data of the hemi-field visual field stimulation.

Factor	Latency		Log amplitude	
	F	p	F	p
Face				
ROI	0.41	0.53	3.10	0.081
Visual field	0.13	0.72	1.84	0.18
Hemisphere	2.06	0.15	0.00	1.00
ROI × visual field	0.28	0.60	1.86	0.18
ROI × hemisphere	0.11	0.75	0.018	0.89
Visual field × hemisphere	160.68	**<.0001**	10.43	**0.0016**
ROI × visual field × hemisphere	0.15	0.69	0.23	0.63
Word				
ROI	2.49	0.12	0.63	0.43
Visual field	2.12	0.15	0.16	0.69
Hemisphere	0.012	0.91	23.05	**<.0001**
ROI × visual field	1.53	0.22	1.38	0.24
ROI × hemisphere	0.0046	0.95	1.05	0.31
Visual field × hemisphere	11.23	**0.0012**	1.57	0.21
ROI × visual field × hemisphere	1.78	0.19	0.00070	0.98

ROI, OA/FA; Visual field, L/R; Hemisphere, LH/RH.

not ROI. There was no significant interaction between ROI and hemisphere. A post hoc analysis revealed that the amplitudes in the LH were significantly larger than those in the RH both in the OA and FA.

3.4.2. *Effects of hemi-visual field stimulation*

For the latency of the M170, there was no significant main effect. However, there was a significant interaction between visual field and hemisphere (Fig. 5b, Table 2). A post hoc analysis confirmed that the latencies of the contralateral hemisphere were significantly shorter than those of the ipsilateral hemisphere in the OA and FA. With respect to amplitude, there was a significant effect of hemisphere. A post hoc analysis showed that the amplitudes of left OA and FA were significantly larger than those of right ones.

4. Discussion

To explore hemispheric specialization for face and word recognition, ERFs were recorded in a group of young adults while they passively viewed faces and words presented in each hemi-field as well as in the CVF. We hypothesized that we would find a RH advantage for faces and LH advantage for words as previously found in the literature. Nevertheless, we found only a LH advantage for words. We will discuss the neural correlates of these somewhat confounding results here in due course.

4.1. *Face recognition*

Our findings in relation to face processing are summarized as follows: 1) the M170 amplitude was not lateralized irrespective

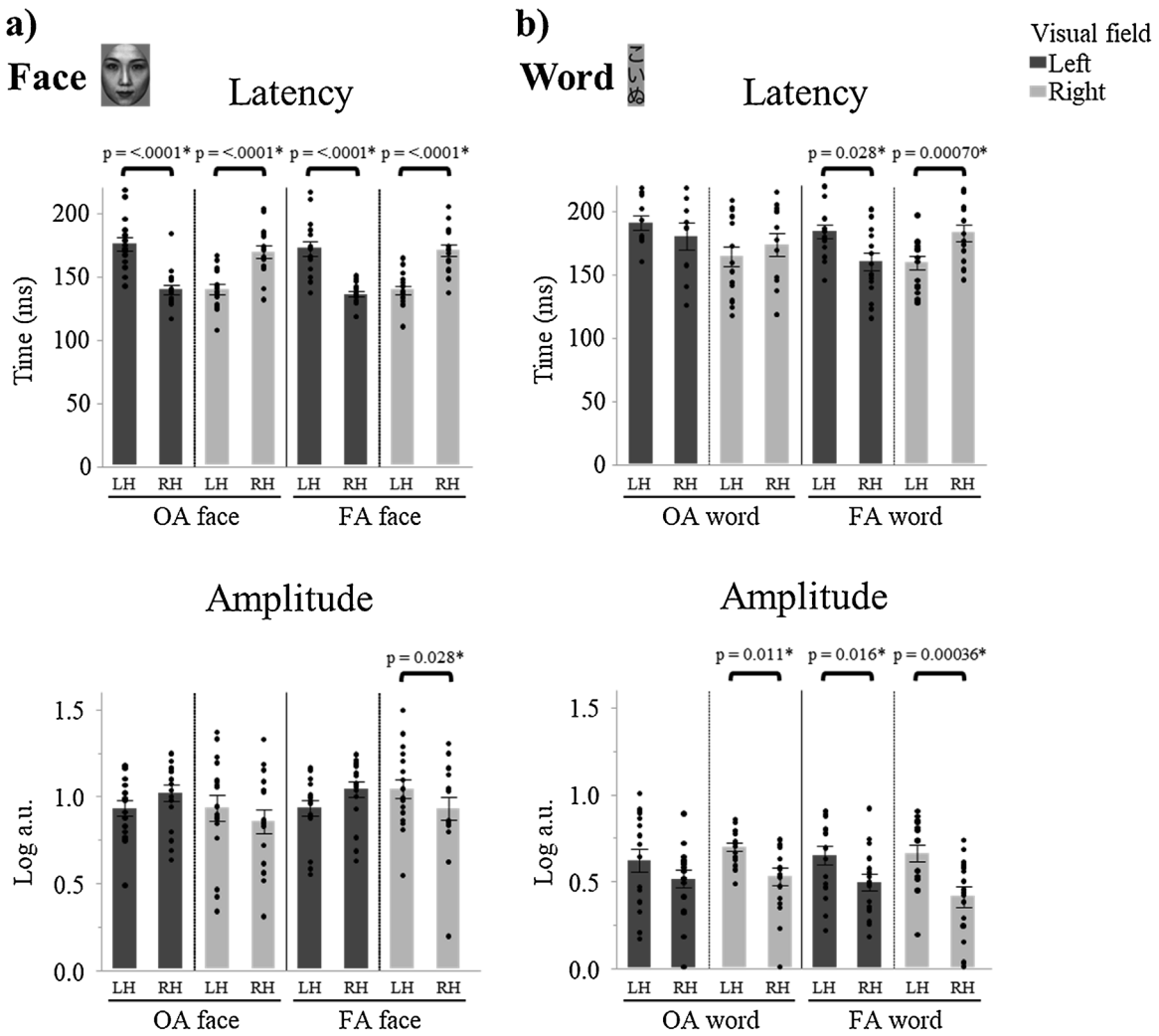

Fig. 5. Effects of the hemi-field stimulation on the M170 responses to face (a) and word (b) stimuli. a) In the face condition, the latencies of the contralateral hemisphere were significantly shorter than those of the ipsilateral hemisphere both in the OA and FA. In contrast, there were no significant differences in the amplitudes between the two hemispheres for both the OA and FA. b) In the word condition, the latencies of the contralateral hemisphere were significantly shorter than those of the ipsilateral hemisphere except for right visual field stimulus in the OA. Similarly, the amplitudes of the left hemisphere were significantly larger than those of right ones, regardless of visual field stimuli in the FA.

of the stimulated visual field but CVF stimulation showed a right lateralized response in the OA, 2) the FA amplitude tended to be larger than that of the OA, and 3) contralateral latency was significantly shorter than that of the ipsilateral one. Therefore, a RH advantage for faces was not fully established. Interestingly, the right lateralized response was caused by CVF stimulation in the OA, which suggests that face perception needs interhemispheric connectivity between the hemispheres. Alternatively, centralized stimuli are processed more effectively due to acuity and attentional factors.

Although bilateral lesions may cause more severe impairments in face recognition than unilateral lesion, the RH superiority of face recognition is well established (Bukowski et al., 2013). In previous MEG studies on face perception, the M170 has been found to be involved in the identification of faces but not in the identification of any objects of expertise (e.g. hand and car) (Watanabe et al., 1999, 2005; Tarkiainen et al., 2002; Xu et al., 2005). Watanabe et al. (2005) recorded MEG in response to each hemi-field stimulation and found no amplitude differences across the stimulated half field. However, face processing occurred either more bilaterally or with RH predominance through CVF stimulation (Tarkiainen et al., 2002; Watanabe et al., 1999, 2005; Xu et al., 2005). Therefore, our results are in accord with the results of previous MEG studies. We suggest again that face perception needs interhemispheric connectivity between the two hemispheres.

4.2. Word recognition

Our findings in relation to word processing are summarized as follows: 1) the M170 amplitude was lateralized in the LH irrespective of the stimulus visual field, 2) Contralateral latency was significantly shorter than that of the ipsilateral one. These findings suggest the LH advantage for words. In previous MEG studies on word perception, the M170 has been found to be involved in letter-string analysis (Pammer et al., 2004; Tarkiainen et al., 2002; Hauk et al., 2012). Based on these studies, word recognition is known to occur with LH predominance in CVF stimulation. However, there have been no previous studies that have performed either RVF or LVF stimulation to separate the functions of both hemispheres. We are the first to demonstrate the presence of LH predominance using half field stimulation.

Unlike many other languages that use a single script, Japanese language system consists of multiple scripts including 'Kana (Hiragana and Katakana)' and 'Kanji' (Kawabata Duncan et al., 2014). The former two scripts are based on phonetic symbols, and each symbol represents a syllable while Kanji have their own meanings. Kana is

generally less visually complex than the majority of those used in Kanji. We used Hiragana because it requires more left-lateralized brain function for alphabetic or syllabographic scripts (including Kana) than Kanji (Sasanuma et al., 1977). The LH advantage for Kana in this study is consistent with the results of a previous study on the alphabet letter-string (Tarkiainen et al., 2002). The VWFA (Cohen et al., 2000) is located in the left inferotemporal region and known to respond more to visual words than to any other category of stimuli. It is known that learning to read results in the progressive development of the VWFA (Cohen and Dehaene, 2004). Therefore, the VWFA acts as a rapid gateway to higher cognitive processing. In terms of neuromagnetic responses to half field stimulation, the importance of LH for word recognition is verified in this study.

4.3. Importance of inter-hemispheric connectivity

Visual cognition may be conceptualized as a distributed but integrated system (Behrmann and Plaut, 2013). Face and word recognition are performed by a distributed network of partially specialized cortical regions, though the degree of specialization is considerably varied across individuals. Even though word and face processing appear to occur in completely unrelated visual domains, some previous works have reported that these domains may not be independent. Namely, the hemispheric function of face recognition and of word recognition does not emerge independently, and that word lateralization may be ahead and urge later face lateralization (Dundas et al., 2014). The neural recycling hypothesis (Dehaene and Cohen, 2007) suggests that the acquisition of new cognitive abilities, such as reading, will result in the recycling of previously established neural circuits. In both face and word recognition, we require the ability to distinguish fine differences. Therefore, according to this hypothesis, there is a possibility that in acquiring reading ability, face-related areas also function in relation to word recognition.

Such a competitive interaction between faces and words supports the idea that strongly interconnected mechanisms underlie the functional architecture of the human ventral temporal cortex. Additionally, there exists a relationship between handedness and face lateralization (Bukowski et al., 2013), possibly due to the robust relationship between handedness and language lateralization (Knecht et al., 2000b; Knecht et al., 2000a). In accordance, cases of prosopagnosia due to unilateral left fusiform gyrus lesions have mostly been reported in left-handed participants (Barton, 2008; Mattson et al., 2000; Eimer and McCarthy, 1999).

Despite hemispheric dominance, activation has often been bilaterally observed for both categories (Puce et al., 1996; Kanwisher, 2017). For example, many fMRI and ERP studies have shown bilateral activation for words and for faces, though usually with greater activation for words on the LH and faces on the RH of the brain (Hasson et al., 2002; Kanwisher et al., 1997; Kronbichler et al., 2004; Nestor et al., 2011; Price and Mechelli, 2005; Puce et al., 1996; Sergent et al., 1992; Tagamets et al., 2000). Consistent with this, prosopagnosia is more severe following bilateral than unilateral right lesions (Barton, 2008), implicating a LH contribution to face recognition, and prosopagnosia has been reported in a right-handed participant subsequent to a left hemisphere lesion (Anaki et al., 2007; Mattson et al., 2000; Gainotti and Marra, 2011). Except for few case reports that described pure alexia in a right-handed participant after a unilateral right occipitotemporal lesion (Davous and Boller, 1994; Ogden, 1984), it is well established that the LH appears to play a functional role in word recognition in right-handed adults (Behrmann and Plaut, 2013; Cohen and Dehaene, 2004). Overall, regarding facial recognition, data suggest that this was originally conducted in both hemispheres. However, as a result of acquiring reading ability, a part of the face-related brain area later also took on a word recognition role. Therefore, facial recognition is poor in terms of laterality but word recognition has remarkable LH laterality.

5. Conclusions

We observed a larger M170 in the LH for words in the RVF stimulation condition. Unexpectedly, a larger M170 in the RH for faces was not found in the LVF stimulation condition. These findings suggest that the hemispheric organization of face recognition is different from that of word recognition in terms of specificity. We propose that the word pathway is acquired later in life. However, bilateral paths are necessary for face recognition in early life.

Declaration of Competing Interest

None.

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