An MEG study of cortical responses related to subjective preference for different regularities of a fluctuating light

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Human cortical activities in regard to flickering lights with different regularities of luminance fluctuations were investigated. The regularities of luminance fluctuations were changed by utilizing a sinusoidal wave of 1-Hz frequency and band noises with different bandwidths centered on 1 Hz. A pair of the most- and less-preferred stimuli, which were selected according to the results of subjective preference tests, was presented to the subject via a single, green light-emitting diode (LED). Whole-head magnetoencephalography (MEG) signals in the theta, alpha, and beta ranges were analyzed by autocorrelation function (ACF). Significant results were found regarding the alpha activity over the left occipital region: the values of effective duration (τ_e) of the MEG signals in the alpha range were significantly larger for the most-preferred stimuli than those for the less-preferred stimuli. Given that the value of τ_e represents a repetitive feature contained within the signal, the results indicate that the stable rhythm of the alpha activity over the left occipital region persists longer for more-preferred regularity of a fluctuating light.

Keywords: fluctuating light, subjective preference, magnetoencephalography, brain rhythm, autocorrelation function

1. INTRODUCTION

Both subjective and objective evaluations of the environment need to be considered for designing the preferable visual environment. With regard to the period of a sinusoidal flickering light as a typical temporal factor, the scale value of subjective preference has been evaluated (Soeta et al., 2002a). Their results showed that the most-preferred period was approximately 1.0 s. In addition, to obtain a more objective indication of the observer's subjective preference for the visual environment, the relationship between the scale value of subjective preference and cortical alpha activity over the occipital area has been investigated by electroencephalography (EEG) and magnetoencephalography (MEG) (Soeta et al., 2002a; Soeta et al., 2002b). In these studies, the factors extracted from the autocorrelation function (ACF) of the alpha activity were analyzed. The results on the effective duration of the envelope of the normalized ACF (τ_e), which indicates the rhythmic stability of the alpha activity, showed that a stable cortical rhythm in the alpha range persisted longer under the most-preferred stimulus condition than the less-preferred stimulus condition. Such a difference of τ_e value was especially observed over the left occipital area. Another study on EEG responses to a visual target with sinusoidal movement (reciprocation) in the horizontal direction analyzed the values of τ_e over the occipital area in different frequency bands corresponding to theta, alpha, and beta ranges (Okamoto et al., 2003). The result that the cortical rhythm for the most-preferred stimulus was more stable was only shown for the case of alpha activity. This behavior of cortical activity in the alpha range relating to subjective preference has also been reported in studies on physical factors in the sound field (Ando and Chen, 1996; Chen and Ando, 1996; Soeta et al., 2002c; Sato et al., 2003; see also Ando, 2003).

To obtain a more preferable condition of flickering light than that with the above mentioned sinusoidal signal of 1.0 Hz, a degree of regularity in the fluctuating light was introduced (Soeta et al, 2005). It was found that subjects preferred a flickering light that was neither completely periodic nor completely random. And their results showed that subjective preference was highest when the amplitude of the first peak in the normalized ACF of the luminance (ϕ_1) was approximately 0.5.

Previous studies have shown a positive correlation between the scale value of subjective preference for a visual stimulus with a regular change of a physical property over

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time and the rhythmic stability of the alpha activity over the occipital area. To obtain an objective indication of the observer's subjective preference for a visual stimulus whose physical property changes irregularly over time, the present study examined whether or not the alpha activity over the occipital area is more stable under the preferred condition of flickering light with luminance variation containing irregularity. In addition, using a visual stimulus with an irregular change of a physical property allows us to reconfirm that the rhythmic stability of the alpha activity is changed by the subjective preference, but not simply by the regular visual stimulation.

Prior to measuring cortical activities, individual scale values of subjective preference were evaluated. MEG was then recorded during the presentation of a pair composed of the most-preferred stimulus and the less-preferred stimulus, which were selected for each subject according to a certain individual difference of the scale value of subjective preference. To confirm the validity of focusing on the occipital alpha activity, the MEG signals obtained from other cortical areas were also analyzed by ACF.

2. METHODS

2.1. Stimuli

The stimuli were presented to the subjects via a green light-emitting diode (LED) that subtended 0.3° of the visual angle. The LED, mounted on a matt-black display panel, was located in front of each subject's nasion at a viewing distance of 1.4 m.

The normalized ACF of the flickering light signal is defined by

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)}, \qquad (1)$$

where

$$\Phi(\tau) = \frac{1}{2T}\int_0^{2T} L(t)L(t+\tau)dt, \qquad (2)$$

and, 2T is integration interval, τ is time delay, and L(t) is luminance of a light signal.

Four physical factors were extracted from the ACF: (1) energy represented at the origin of delay, $\Phi(0)$; (2) effective duration of the envelope of the normalized ACF, τ_e; (3) the amplitude of the first maximum peak of the normalized ACF, ϕ_1; and (4) its delay time, τ_1 (Ando, 1998). These factors were controlled as explained below.

The value of τ_1 corresponds well to the fundamental frequency of flickering light (Fujii et al., 2000) and the value of ϕ_1 is regarded as the strength of the fundamental frequency. When the band noise is used as a source signal, the value of τ_1 corresponds to the center frequency of the band noise and the value of ϕ_1 decreases as the bandwidth increases. To vary the value of factor ϕ_1, the visual stimuli consisted of a sinusoidal wave with frequency of 1 Hz (ϕ_1 = 1.0) and band noises with four different bandwidths centered on 1 Hz; thus, ϕ_1 = 0.7, 0.55, 0.4, and 0.3 and the value of τ_1 = 1 ms for all stimuli. These values were selected according to previous studies (Soeta et al., 2002a; Soeta et al., 2005). The value of τ_e, which represents a repetitive feature contained within the source signal, and ϕ_1 have a certain degree of coherence. Accordingly, the ϕ_1 value was chosen to represent the regularity of fluctuation of the luminance patterns in the time domain. The value of $\Phi(0)$ for all of the stimuli was controlled so that it would be fixed. All of the stimuli had the same mean luminance (10 cd/m^2). The duration of a stimulus was 4.0 s. Figure 1 shows an example of the normalized ACF of a visual stimulus analyzed with 2T = 4.0 s.

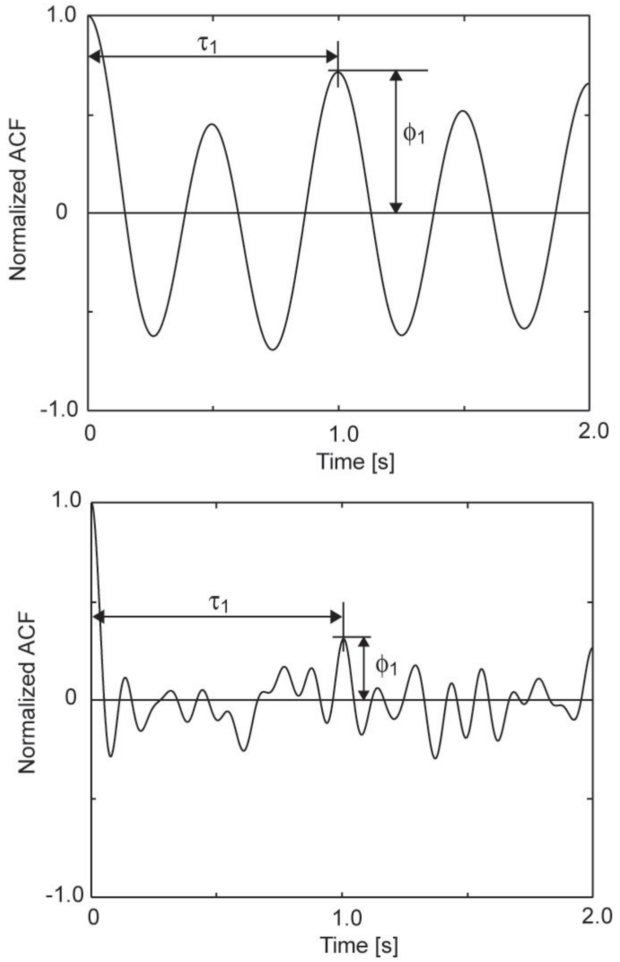

Fig. 1. An example of normalized ACF of a visual stimulus and definition of factors ϕ_1 and τ_1. Top panel: ϕ_1 = 0.7, bottom panel: ϕ_1 = 0.3.

2.2. Subjects

Ten healthy right-handed male subjects (22–27 years old) with normal or corrected-to-normal vision participated in the study. This study had prior approval by the Ethical Committee of Kansai Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Japan, and written informed consent was obtained from each subject after an explanation of the nature and purpose of the investigation.

2.3. Subjective preference tests

The paired-comparison test was conducted in a dark sound-proof room to evaluate the scale value of subjective preference for each stimulus. The interval between each stimulus of the pair was 2.0 s, while that between pairs was 4.0 s. Subjects were instructed to fixate on the visual stimuli, judge which of the two stimuli in the pair they preferred, and respond by pushing one of two keys. Each pair was presented 10 times per subject. The scale value of the subjective judgments of each subject was obtained according to Case V of Thurstone's theory (Thurstone, 1927).

The top of Fig. 2 shows the scale values of subjective preference as a function of ϕ_1 extracted from the ACF of the fluctuating visual signal (ten subjects). The most-preferred conditions of individuals ($[\phi_1]_p$) were estimated as listed in Table 1, and at the bottom of Fig. 2, the scale values are plotted as a function of $\phi_1/[\phi_1]_p$. Preferences declined as the flicker was made either more random (lower ϕ_1) or more regular (higher ϕ_1), as reported in a previous study (Soeta et al, 2005).

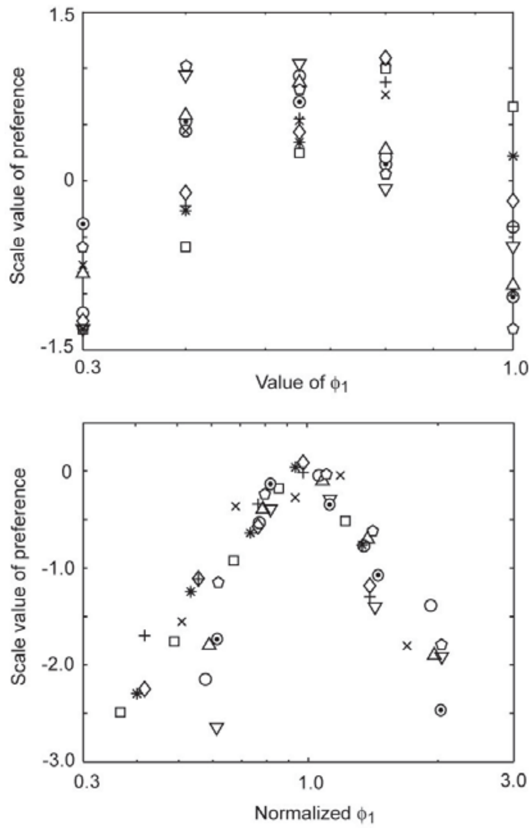

Fig. 2. Scale values of subjective preference for all subjects. Different symbols represent the different subjects. In the bottom panel, the abscissa is normalized by the value of $[\phi_1]_p$, which was estimated by the maximum peak of a polynomial approximation curve to a plot of the individual scale values. The scale values at $[\phi_1]_p$ are adjusted to zero.

2.4. MEG recording procedures

A 122-channel whole-head neuromagnetometer (Neuromag-122™, Neuromag Ltd., Helsinki, Finland) was used in this study. The device measured two tangential derivatives of the magnetic field component at 61 locations over the head (Hämäläinen et al., 1993). The signals were recorded with a band-pass filter for the 0.03–100-Hz frequency band and digitized with a sampling rate of 400 Hz. The recordings of the subjects who participated in the subjective preference test were performed in a magnetically shielded room.

For MEG recording, the most-preferred stimuli were presented as a pair first. The less-preferred ones were then presented. According to the results of the subjective preference

Table 1. The values of ϕ_1 of the stimuli used for the MEG recording.

	Subject									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
The most-preferred stimulus in a pair $[\phi_1]$	0.52	0.59	0.72	0.75	0.82	0.72	0.51	0.49	0.50	0.49
Experiment 1 The less-preferred stimulus in a pair was fixed at $\phi_1 = 0.3$ (low regularity)										
Experiment 2 The less-preferred stimulus in a pair was fixed at $\phi_1 = 1.0$ (high regularity)										

test, $[\phi_1]_p$ as the most-preferred condition and two ends of the range of ϕ_1 (0.3 and 1.0, respectively) as the less-preferred conditions were selected for each of the 10 subjects (Table 1). Paired with the preferred condition, Experiment 1 probed the effect of the more random modulation, while Experiment 2 probed the effect of the regular, sinusoidal modulation. A pair of stimuli was presented with an interval of 2.0 s, and each pair was presented 30 times with a 2.0 s repeated interval. The differences of the scale values between the most-preferred stimuli and the less-preferred stimuli were 1.90±0.32 and 1.43 ±0.40 for Experiments 1 and 2, respectively. Two kinds of experiments to determine whether the MEG activities were varied by the scale value of subjective preference or by the simple ϕ_1 values were conducted.

2.5. MEG analysis procedures

The MEG analyses were performed on data within the following frequency ranges: 4–8 Hz (theta), 8–13 Hz (alpha) and 13–30 Hz (beta). For each stimulus presentation, ACF was obtained from the time-windowed MEG signal at each MEG sensor as shown in Fig. 3. The four factors extracted from the ACFs of MEG signals were analyzed and the factors for each stimulus condition were averaged together. For the ACF analysis, the integration interval 2T (window length) was set at 2.5 s, which is considered to be the duration needed for subjects to make subjective preference judgments (Chen and Ando, 1996). The bottom panel of Fig. 3 demonstrates an example of the analyzed ACF of the MEG signal in the alpha range. The ACF is plotted on a logarithmic scale as a function of its delay time. In most cases, the envelope decay of the initial part of the normalized ACF can be fitted to a straight line ranging from 0 to −5 dB, and the effective duration τ_e of the ACF can be easily obtained from the decay rate extrapolated at −10 dB.

As shown at the top of Fig. 4, MEG sensors covering the entire head of the subjects were divided into ten groups related to different cortical regions: the frontal, central, temporal, parietal, and occipital regions of the left and right hemisphere, respectively, and each group had six pairs of sensors. Grouping sensors reduced information on the spatial positions given by the 122 sensors of a whole head magnetometer, and the broadly distributed effect of the stimulus condition was evaluated.

Initially, the effect of stimulus condition on ACF factors of the MEG signals was assessed in each cortical region. A separate analysis of variance (ANOVA), with stimulus condition and frequency band as factors, was performed for each MEG sensor group. A significance level of 0.005 was used for each ANOVA to control Type I error rate. In addition, a nonsignificant trend in change of the analyzed factor of the MEG signal was also considered if the *P* value was less than 0.05. As a further analysis to investigate in greater detail the effect of the stimulus condition, the MEG sensor group, in which a tendency for the analyzed factor to change according to stimulus conditions was observed in both experiments, was then subdivided.

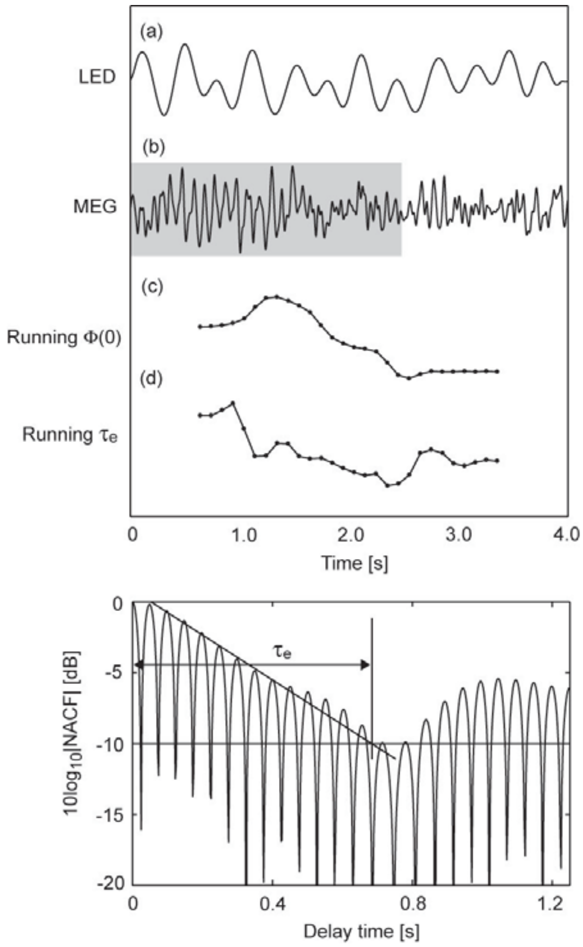

Fig. 3. Top panel: examples of waveforms of a visual stimulus and MEG responses for a presentation of this stimulus. (a) The luminance waveform of a flicker (ϕ_1 = 0.55). (b) MEG response between the stimulus onset and offset, obtained from one sensor. The windowed part (shaded area) was used for the ACF analysis after each frequency range was extracted. (c, d) The running average power ($\Phi(0)$) and running τ_e of the MEG response (shown in (b)) in the alpha range. The integration interval was 1.25 s and the running step was 0.1 s. Bottom panel: ACF waveform of the MEG signal ((b) in the top panel) in the alpha range and definition of the effective duration of ACF (τ_e).

3. RESULTS

Figure 4 shows the results of averaged values of $\Phi(0)$ for Experiments 1 and 2. The $\Phi(0)$ values were normalized by the

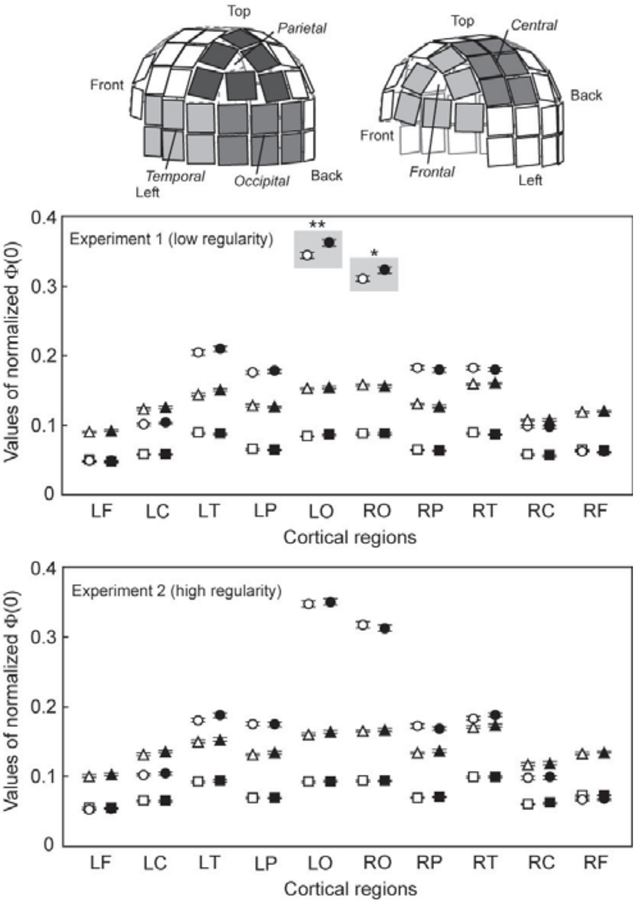

Fig. 4. The MEG sensor arrays viewed from the left posterior and left anterior sides are shown at the top and the left five MEG sensor groups are depicted. The sensors on the right side are divided in the same way as those on the left side. Panels show values of Φ(0) averaged across all subjects in the theta (square), alpha (circle), and beta (triangle) ranges over F (frontal), C (central), T (temporal), P (parietal), and O (occipital) regions. L and R denote the left and the right side. Open and closed symbols indicate the most- and less-preferred conditions, respectively. The shaded areas indicate the significant differences in Φ(0) between stimulus conditions (*P < 0.005, **P < 0.001) and the tendencies for Φ(0) to change according to the stimulus conditions (P < 0.05). The top and bottom represent the results in Experiments 1 and 2, respectively. Error bars indicate SEM.

maximum Φ(0) value in the broad frequency range (4–30 Hz) for each subject. The values of Φ(0) in the alpha range were particularly large over the left and right occipital regions. In Experiment 1, analyses of simple main effects showed the differences of Φ(0) between the two stimulus conditions were significant in these regions. However, significant effects or nonsignificant trends in Φ(0) values related to the stimulus condition were not observed in the other cortical regions. In both experiments, there were significant effects of frequency band in all cortical regions. Tukey's Honestly Significant Difference (HSD) tests showed that the values of Φ(0) in the beta range were significantly larger than those in theta in all cortical regions and those in the alpha range were significantly larger than those in other frequency bands over the temporal, parietal, and occipital regions (P < 0.001).

The results of averaged values of τ_e are shown in Fig. 5. The simple main effects of stimulus condition were significant in the theta range over the left central region and in the alpha range over right temporal region in Experiment 2. The values of τ_e tended to change according to the stimulus conditions over the left central, left temporal, and left occipital regions in Experiment 1, and over left occipital region in Experiment 2. In both experiments, the values of τ_e in the beta range were significantly smaller than those in theta and alpha in all cortical regions (P < 0.001). The values in the alpha range were significantly larger than those in theta over the temporal, parietal and occipital regions, and vice versa over the frontal region (P <0.001).

Figure 6 shows the results of the averaged values of ϕ_1. There was no significant effect of stimulus condition in both experiments. The values of ϕ_1 tended to be affected by the stimulus conditions over the left frontal and the left temporal regions in Experiment 1, and over the right temporal region in

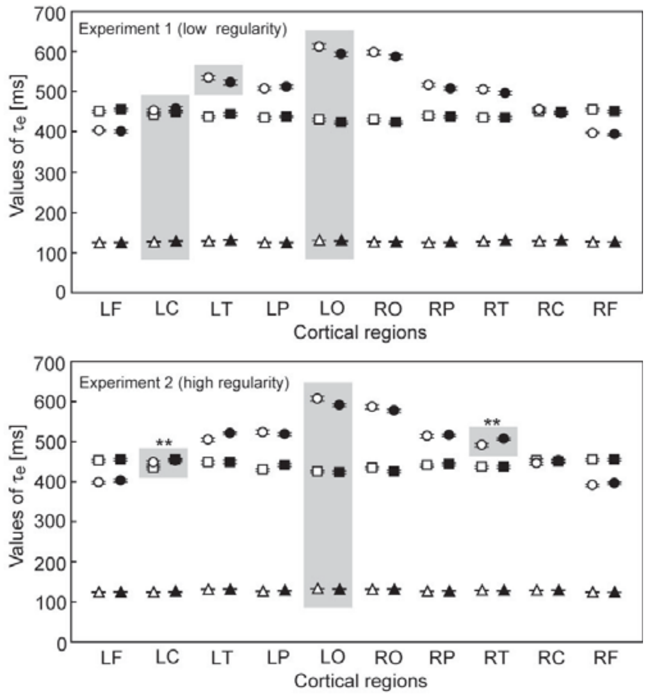

Fig. 5. Values of τ_e averaged across all subjects, arranged as in Fig. 4.

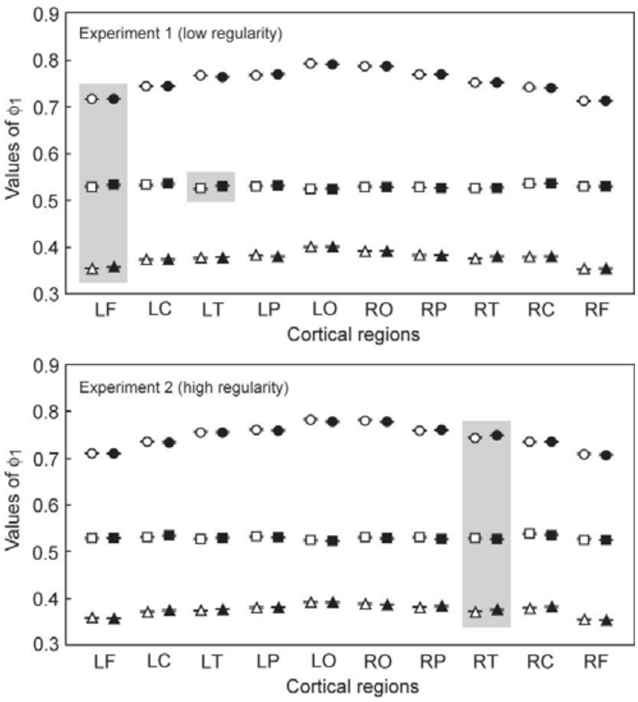

Fig. 6. Values of ϕ_1 averaged across all subjects, arranged as in Fig. 4.

Experiment 2. Similar to the results of τ_e, the values of ϕ_1 in the alpha range were significantly larger than those in theta and beta, and those in theta were significantly larger than those in beta in all cortical regions in both experiments ($P < 0.001$).

For the value of τ_1, since it corresponds to the center frequency of each wave, there was no significant effect of stimulus condition or significant effects of frequency band in either experiment. In fact, the values of τ_1 in the theta, alpha, and beta ranges were approximately 0.2 s (5 Hz), 0.1 s (10 Hz), and 0.05 s (20 Hz), respectively.

The initial analyses showed that the τ_e values tended to change according the stimulus conditions in both experiments when MEG sensor groups over the left occipital region and the left central region were analyzed, although the differences of τ_e between different stimulus conditions were not significant. These results indicate that subjective preference was better reflected in τ_e values over left occipital and left central regions than those over other cortical regions. Further analyses were therefore carried out for these two regions.

As shown at the top of Fig. 7, the area over the left occipital region, which is important optically, was divided into three areas, i.e., midline occipital, left occipital and left occipitotemporal regions, and two pairs of MEG sensors were applied to each area. For each frequency range, the values of τ_e in each area were averaged, as shown in Fig. 7. The effects of the stimulus condition and cortical region were assessed by two-way ANOVA. A remarkable result was found in the alpha range, such that the values of τ_e for the most-preferred stimuli were significantly larger than those for the less-preferred stimuli in both experiments ($P < 0.05$). For the theta and beta ranges, however, the significant effects of stimulus condition were not observed. The effects of cortical region were significant for the alpha and beta ranges in both experiments ($P < 0.01$).

For the data in the theta range obtained from the MEG sensor group covering the left central region, in both experiments, initial analyses showed that the values of τ_e for the

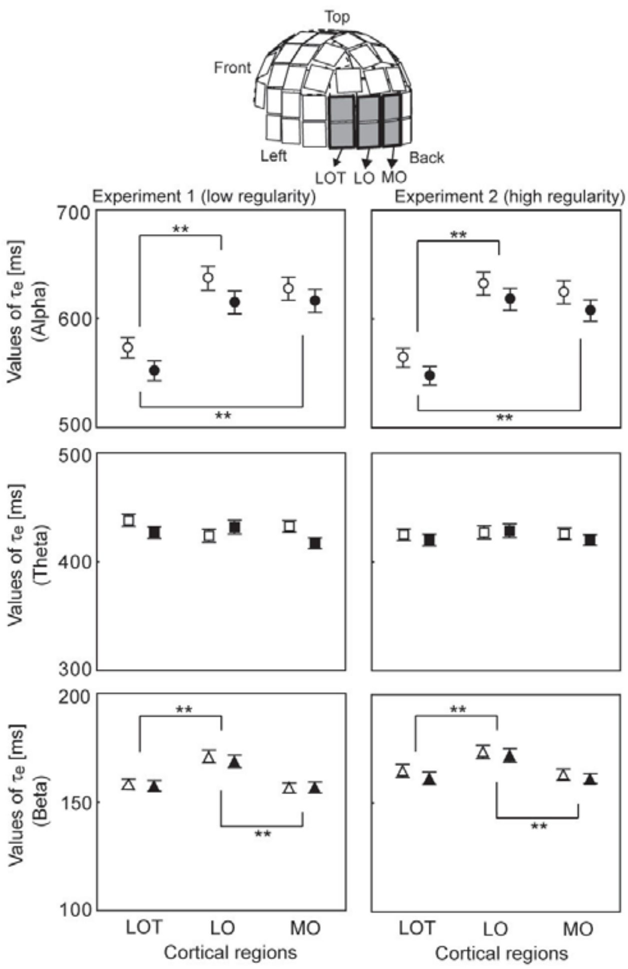

Fig. 7. The MEG sensors for the further analyses are shown at the top (MO = midline occipital region; LO = left occipital region; LOT = left occipitotemporal region). Panels in the top, middle and bottom rows show the averaged values of τ_e in the alpha, theta, and beta ranges, respectively. Results in Experiments 1 and 2 are shown in the left and right panels, respectively. Open and closed symbols indicate the most- and less-preferred conditions, respectively. Error bars indicate SEM (*$P < 0.05$, **$P < 0.01$).

less-preferred stimuli were significantly larger than those for the most-preferred stimuli. For further analyses, the region was also divided into three areas and the τ_e values for the theta range were averaged in each area. Use of two-way ANOVA showed that the effect of stimulus condition was significant in Experiment 2 ($P < 0.01$) but not in Experiment 1 and the significant effect of the cortical area was observed in Experiment 1 ($P < 0.05$) but not in Experiment 2.

4. DISCUSSION

4.1. Effect of subjective preference on the ACF factors of MEG

4.1.1. τ_e value of MEG signals

When the MEG data over the left occipital region were analyzed, the averaged τ_e values of the MEG signals in the alpha range obtained for the most-preferred stimuli were significantly larger than those for the less-preferred stimuli in both Experiments 1 and 2 (Fig. 7). This result indicates that the values of τ_e were affected by subjective preference, but not by regularity, which is just a physical property of the stimulus. The value of τ_e is an indication of the stability of rhythmic cortical activity. This result therefore indicates that, with regard to changes of the regularity of a fluctuating light, the stable rhythm of alpha activity persists longer under the more-preferred stimulus condition. Studies related to mental activities have shown the association between alpha activities and higher brain functioning (Kolev, et al., 1999); such a tendency for the τ_e value of alpha activity over the occipital area to increase under the preferred condition has also been found in previous EEG and MEG studies (Soeta et al., 2002a; Soeta et al., 2002b; Okamoto et al., 2003).

In the present study, a tendency for τ_e values in the alpha range to increase under the most-preferred condition were observed more obviously over the left occipital region than over the right occipital region (Fig. 5). This may be the result of hemispheric specialization with regard to changes of the temporal factor of the visual stimulus. Differential patterns of alpha asymmetry are thought to reflect predominance of the activities in left- and right-sided cortex (Merrin and Floyd, 1997). A left-hemisphere specialization for temporal processing has previously been proposed with regard to research on auditory stimuli (Ando and Kang, 1987) and on gap-detection tasks in the auditory or visual modalities (Nicholls, et al., 2002). Previous studies have also reported that the τ_e values of alpha activity were affected by left hemispheric specialization when the temporal frequency of a visual stimulus was varied (Soeta et al., 2002a; Soeta et al., 2002b).

Further analyses carried out in the present study showed that the values of τ_e in the alpha range in the left and midline occipital regions were significantly larger than that in the left occipitotemporal region in both experiments as shown in Fig. 7. With regard to subjective preference for visual motion, previous work has indicated that the τ_e in the alpha range in the occipitotemporal area was as great as that in the occipital area (Okamoto et al., 2003). This may have been caused by differences in the stimuli used in each study, since motion stimuli have been found to activate a more lateral cortical area than non-motion stimuli (Probst et al. 1993). Furthermore, the motion stimuli comprised a wider visual angle compared to the stimuli used in the present study. Additionally, the previous study showed that the τ_e value in the alpha range in the left occipital area was significantly larger than that in the midline occipital area (Soeta et al., 2002b). Although not significant, the same tendency was shown in this study (Fig. 7).

In terms of the theta activity over the left central region, a result contrary to that for the alpha activity over the left occipital region was obtained in the initial analyses: the averaged τ_e values for the less-preferred stimuli tended to be larger than those for the most-preferred stimuli in both Experiments 1 and 2. Results from several previous studies have suggested that the theta rhythm observed over the midline frontal area is related to mental calculation and meditative concentration (Sasaki et al., 1996; Kubota et al., 2001), and the power increases with increasing task difficulty (Kahana et al., 1999). (The frontal area generally indicates the cortical area in front of the central sulcus, and the anterior and posterior parts of the frontal area are involved in the regions named in this study as the frontal and central regions, respectively.) The present results suggest the possibility that the mental state induced by the visual stimuli affects the theta rhythm, and the τ_e value of the rhythm correlates negatively with subjective preference. However, the effect of stimulus condition was not observed in the anterior frontal area and it was not significant in the further analyses of Experiment 1. Further research is needed in order to form conclusions regarding the relationship between subjective preference and the τ_e value of the theta rhythm in the frontal area.

4.1.2. Other ACF factors ($\Phi(0)$, ϕ_1, τ_1) of MEG signals

For the other ACF factors ($\Phi(0)$, ϕ_1, τ_1), there was no MEG sensor group in which the stimulus conditions tended to affect the factors in both experiments. A previous MEG study reported that values of τ_e and ϕ_1 of alpha activity in the occipital area showed a positive correlation with subjective preference, although τ_e was associated with better subjective preference, in comparison to ϕ_1 (Soeta et al., 2002b). In the present study, the averaged ϕ_1 values in the alpha range for the most-preferred stimuli were slightly larger than those for the less-preferred stimuli over the occipital region (Fig. 6).

4.2. Effect of frequency band on the ACF factors of MEG

The MEG average power ($\Phi(0)$) in alpha was significantly larger than that in other frequency bands over the temporal, parietal, and, especially, occipital regions in both experiments. Previous studies have also reported that cortical oscillations in the alpha frequency range showed a maximum power over occipital areas and progressively decreased towards anterior areas (Rodin and Rodin, 1995) independently of the brain state (Cantero et al., 1999). Generally, there is a certain degree of coherence between τ_e and ϕ_1. Thus, for both values in all cortical regions, except the central and frontal regions, those in the alpha range were largest, and those in the theta range were smallest. This indicates that the alpha activity had the strongest rhythmic stability among the three frequency ranges in those regions. On the other hand, over the central and frontal regions, the τ_e values in the alpha range were not the largest. Considering the decrease of $\Phi(0)$ over the central and frontal regions form the occipital region (Fig. 4), this may be because the stability of the rhythm of alpha activity decreased due to the weak alpha activity.

4.3. Effect of simple regularity on MEG average power

The difference between the visual cortex response in the case of periodic and aperiodic visual stimulations has been investigated (Parkes et al., 2004). Their results showed that compared to the MEG response to the periodic stimulus, that to the aperiodic stimulus showed generally increased power over a broad frequency band. They concluded that the result of the MEG power over a broad frequency band is due to increased neuronal firing for the broad range of frequencies present in the aperiodic stimulus. In the present study, over the occipital region involving the visual cortex, the MEG response in the alpha range for the lower-regularity stimulus had significantly greater power than that for the middle-regularity (preferred condition) stimulus (Experiment 1). This result could be caused by the stimulus that contained a broader range of frequencies, although there was no significant difference between the MEG power for the middle-regularity and that for the higher-regularity stimuli (Experiment 2). Such a tendency of MEG power that was found only in the alpha range was due to the fact that the alpha was the predominant frequency band over this region. In addition, this interpretation of MEG power is in agreement with the present result that $\Phi(0)$ is not directory associated with subjective preference.

5. SUMMARY

Human MEG responses related to subjective preference for light with different regularities of temporal fluctuation were investigated by autocorrelation analysis. The MEG signals at different locations and in different frequency bands were analyzed. The analysis results showed that the τ_e values of the alpha activity observed over the left occipital region were significantly larger for the most-preferred stimuli than those for the less-preferred stimuli. This result indicates that with regard to changes of the regularity of a luminance fluctuation, the rhythmic alpha activity over this region is more stable under the more-preferred stimulus condition.

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