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Conference Paper · October 2007

DOI: 10.1109/SICE.2007.4421455 · Source: IEEE Xplore

SICE Annual Conference 2007
Sept. 17-20, 2007, Kagawa University, Japan

Effects of Light Stimulus Frequency on Phase Characteristics of Brain Waves

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Abstract: Dependence of phase response of electroencephalogram (EEG) on stimulus light frequency is investigated under the condition of the stimulus frequency in the range from 5 to 20 Hz for clarifying the effect of the entrained alpha wave to the response of the EEG. Under the flicker stimuli the frequency of which is less than 8 Hz, the response of EEG to the stimuli is rather disordered; the phase of the EEG synchronized to the stimuli (steady-state visually evoked potential, SSVEP) complicatedly fluctuates with time. However, under the condition that the stimulus frequency is in the range of the alpha wave (8-13 Hz), the phase of the SSVEP is considerably stabilized. The phase of the SSVEP forms the anti-phase relationship between the occipital and frontal lobes. The spatial phase structure of the SSVEP for a half of subjects shows a property of a standing wave, while the phase structure for the rest of subjects belongs to a traveling wave. Such phase properties agree with those of the spontaneous alpha waves for most of the subjects. Under the condition of the stimulus frequency higher than the alpha wave range, the SSVEP is similar to the traveling wave for most of the subjects. These results suggest that the spatial phase structure of the SSVEP is significantly affected by the alpha wave.

Keywords: Brain wave, Flicker stimuli, Entrainment, Steady-state visually evoked potential, Phase

1. INTRODUCTION

The alpha wave, the most prominent component in the human electroencephalogram (EEG) in the wake state, has been studied by many researchers for a long time, but its underlying mechanism has not been elucidated well but still controversial. It is very useful to clarify the underlying mechanism for the development of not only an automatic clinical diagnosis from the EEG but also a new communication tool for people with heavy physical disabilities, namely, a brain-computer interface [1].

The nonlinearity of the alpha wave is evidenced by the entrainment to flicker stimuli for which the frequency of the alpha wave is shifted and locked to the frequency of the flicker stimuli under the condition that the stimulus frequency is set in the range of the alpha wave [2,3]. Dependence of the spatiotemporal properties of the alpha wave on the stimulus intensity and stimulus color-alternation has provided useful information on the nonlinear dynamics of the alpha wave [4,5].

Generally, response of EEG to flicker stimuli includes a component which is referred to as the steady-state visually evoked potential (SSVEP), having the same or harmonic frequency as the stimulus frequency [6]. The SSVEP can be elicited by flicker stimuli in wide frequency range from the frequency lower than 5 Hz to that higher than 80 Hz. In particular, the amplitude of the SSVEP is relatively larger under the condition of the stimulus frequency in the range from 5 to 20 Hz.

It is difficult to directly discriminate between the alpha wave and the SSVEP under the condition of the stimulus frequency in the range of the alpha wave (8-13 Hz), characteristics of the SSVEP can be solely investigated under the condition of the stimulus frequency outside the range of the alpha wave. Namely, the entrainment of the alpha wave should be mainly evoked by the flicker stimuli in the frequency range of the alpha wave. Thus, it is possible to consider the effect of the entrained alpha wave on the response of the EEG to flicker stimuli the frequency of which is in the range of the alpha wave by comparing characteristics of the response of the EEG with the characteristics of the SSVEP obtained by the above method.

The SSVEP has been understood in relation to cognitive process, but its underlying mechanism is also veiled. Silberstein et al. have reported that the SSVEP has a property of traveling wave for 40 % of 40 subjects, while it shows a property of standing wave for 30 % [7]. The researchers have tried to explain this result from the viewpoint of the number of dipole layers assumed to be the underlying mechanism of the SSVEP.

Observations of the spatial property of the response of the EEG to flicker stimuli are important for considering the underlying mechanism of the SSVEP as well as the alpha wave [8]. The analogy of the underlying mechanism of the alpha wave with that of the SSVEP should be also considered, since both rhythms have are known to be related to process of visual information from the retina.

Spatiotemporal characteristics of the EEG response including the entrainment of the alpha wave have the possibility of presenting clinically useful information; the amplitude of the SSVEP to temporally modulated patterns of different contrast is remarkable abnormal for luminance contrast in e patients with photosensitive epilepsy[9]. Phase property is also important because the EEG on the onset of the epileptic seizure show the hyper synchronization over the entire scalp.

The present study examines the dependence of the spatial phase structure of the response of the EEG to flicker stimuli on the stimulus frequency. Temporal and spatial variations of the EEG responses at the stimulus frequency and its second harmonics and the spontaneous alpha wave are mutually compared with each other.

2. EXPERIMENTAL METHODS

2.1 Experiment

Spontaneous EEG and stimulated EEG were recorded from 32 healthy subjects aged 20-25 (4 females and 28 males). The electrode arrangement was determined with reference to the Internationa1 10-20 Electrode System. EEGs were derived from fifteen locations (Fp_1, Fp_2, F_3, F_4, F_z, C_3, C_4, C_z, P_3, P_4, P_z, O_1, O_2, T_3, and T_4). The linked-earlobe potential is used as the reference potential for the unipolar derivation. The EEG-5532 (Nihon Koden) was used for recording EEGs at the electrode sites.

The flicker stimuli consisting of flashes of 28 red light emitting diodes (LEDs) were applied to the subjects for approximately 30 s per trial. The stimulus apparatus were located in front of the subject's closed eyes at a distance of 8 cm (Fig. 1). Stimulus frequency is set in the range from 5 to 20 Hz each trial. The wavelength of LED was 660 nm and the stimulus intensity was 35 lx at the position of closed-eyes of the subjects. Informed consent was obtained from all the subjects.

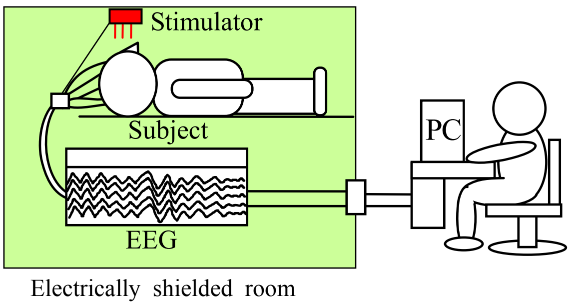

Fig.1 Outline of measurement system

2.2 Analysis

Frequency properties of the EEGs were analyzed using the discrete Fourier transform (DFT), while spatiotemporal dynamics were estimated using the complex demodulation method (CDM). The CDM was used to estimate the phase difference from a reference sinusoidal wave to EEG limited in certain frequency range.

The frequency of the reference sinusoidal wave for the CDM was set at the stimulus frequency f_{stim} for the frequency-locked components of the EEG to the flicker stimuli and $2f_{stim}$ for the second harmonics, whereas it was set at a frequency at which the highest peak stood in the band of the alpha wave in a DFT power spectrum of the EEG for the spontaneous alpha wave.

The frequency-locker components of the EEG mainly include the fundamental SSVEP under the condition of the stimulus frequency outside the frequency range of the alpha wave, but they are affected by the entrained alpha wave under the condition of the stimulus frequency inside the range of the alpha wave. Similarly, the second harmonics of the frequency-locked components may also include the harmonically entrained alpha wave as well as the second harmonic SSVEP when the stimulus frequency is set at 5 or 6 Hz, corresponding to about half of the frequency of the spontaneous alpha wave.

The cut-off frequency of the low-pass filter used for the CDM, denoted by f_c, is fixed at 2 or 0.5 Hz for all the data segments. Thus the phase properties of the elicited EEG the frequency of which is in the range from f_{stim} - f_c to f_{stim} + f_c were analyzed for the frequency-locked components, whereas the frequency components in the range from $2f_{stim} - f_c$ to $2f_{stim} + f_c$ were extracted for the second harmonics.

Spatial phase difference was estimated with reference to the occipital region; $\phi_x - \phi_{O2}$, where ϕ_x denotes the estimated phase of the objective EEG component at the electrode site x. Phase differences between adjacent electrode sites obtained as $\phi_{Fp2} - \phi_{F4}$, $\phi_{F4} - \phi_{C4}$, $\phi_{C4} - \phi_{P4}$ and $\phi_{P4} - \phi_{O2}$ were used for evaluating spatial phase gradient of the elicited EEG.

3. RESULTS

3.1 Frequency spectrum

Figure 2 depicts the power spectra of the occipital EEGs for two subjects. In the free running, the power spectrum for subject A has a large peak at about 10 Hz, indicating that the spontaneous alpha wave with the intrinsic frequency of 10 Hz appears intensively, whereas there stands several peaks in the range from 9 to 12 Hz for another subject B, which suggests that the spontaneous alpha wave consists of several oscillations with independent intrinsic frequency or that the frequency of the alpha wave fluctuates dynamically with time.

Under the condition of 5 Hz stimuli, the spectral amplitude of the SSVEP at the stimulus frequency f_{stim} is small for both subjects. In contrast, the amplitude of the second harmonics at $2f_{stim}$ (=10 Hz) is much larger than that, namely, the amplitude of the fundamental SSVEP, for both subjects. The second harmonic SSVEP may be affected by the harmonic entrainment of the alpha wave, since the frequency of the second harmonics is near the intrinsic frequency of the spontaneous alpha wave mentioned above.

Such superiority of the second harmonics to the fundamental SSVEP is also observed under the conditions of f_{stim} less than 10 Hz for subject A, whereas the spectral amplitude of the second harmonics is much reduced to be less than that of the fundamental SSVEP under the same conditions for another subject B.

The spectral amplitude of the fundamental SSVEP is not larger than that of the spontaneous alpha wave in any case under the above conditions, and the energy of the entire EEG is seen to be attenuated.

A dominantly large peak of the fundamental SSVEP appears at f_{stim} under the condition of f_{stim} = 10 Hz for both subjects. The frequency components other than f_{stim}

seem to be almost attracted to f_{stim} to form the sharp peak. Under the conditions of f_{stim} =11 Hz for both subjects, the dominant sharp peak also emerges at f_{stim} in each spectrum, but the peaks around 10 Hz, due to the spontaneous alpha wave, are still retained. This difference may reflect the intensity of the entrainment of the alpha wave to 11 Hz stimuli.

Moreover, under the conditions higher than 11 Hz, the amplitude at f_{stim} is reduced to be smaller than the peaks of the spontaneous alpha wave near 10 Hz. The spectral peak of the second harmonics is not clearly seen under these conditions, indicating very weakly elicited component.

Under the flicker stimuli higher than 15 Hz, the spectral amplitude of the fundamental SSVEP further decreased with increasing f_{stim} and it is comparable to the second harmonics.

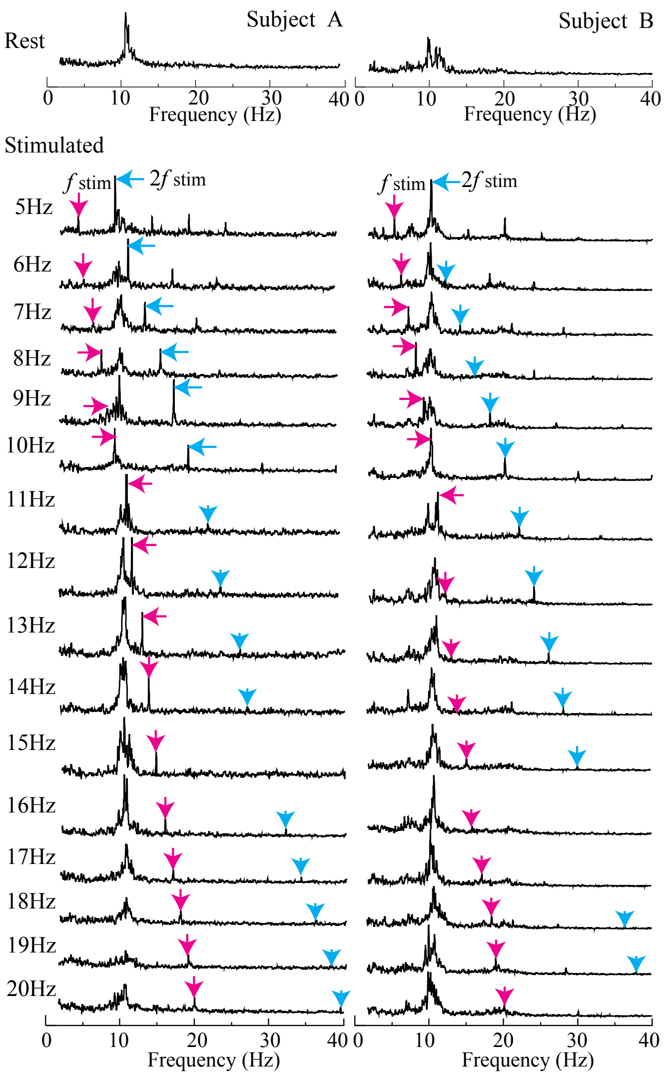

Fig. 2 Power spectra of occipital EEGs for two subjects (A and B) at rest (top) and under stimuli under the conditions of the stimulus frequency in the range from 5 to 20 Hz. Data length used for the DFT analysis is 20 s.

3.2 Spatial Phase structure

- Spontaneous alpha wave fundamental SSVEP -

Figure 3 illustrates the histograms of the phase difference of (a) the alpha wave and the fundamental SSVEP under (b) 5, (c) 10, (d) 11 and (e) 15 Hz, with reference to the right occipital lobe for the two subjects. The histograms of spatial phase difference of the spontaneous alpha wave for subject A have a large gap in an area between the central and frontal regions, indicating a property of the standing wave (Fig. 3(a)).

The peak of the spatial phase difference is however increased monotonously from the parietal to frontal regions (from the top to bottom in the right-hand side of Fig. 3(a)) and has no large shift for subject B. This phenomenon is commonly seen in the traveling wave. Note that most of the counts of the spatial phase difference between the occipital lobe and frontal pole are concentrated near the +180 or -180 deg, namely, the anti-phase relationship, referred to as the phase reversal, which is similar to the histograms for subject A.

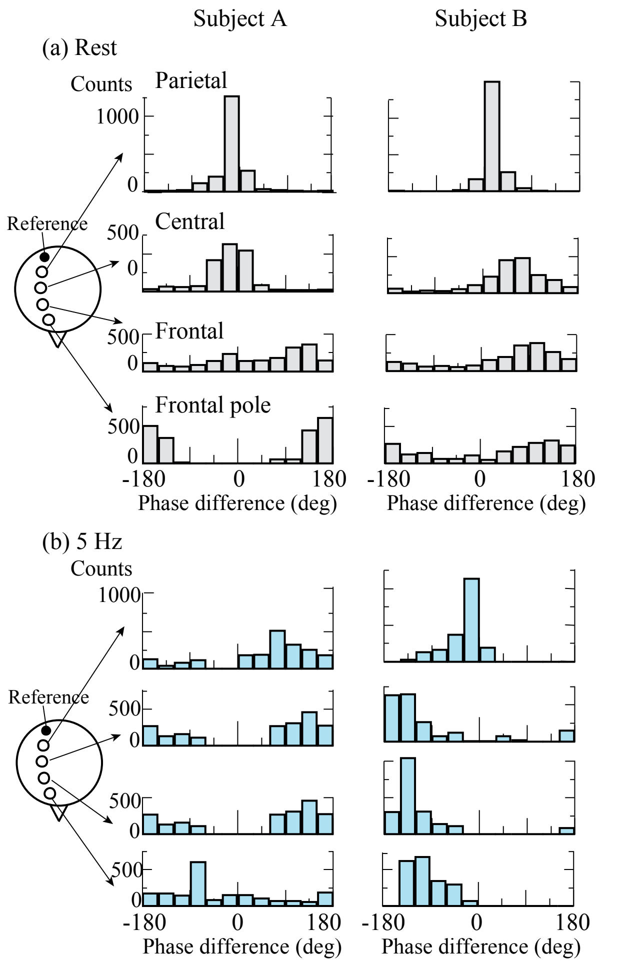

Fig. 3 Histograms of spatial phase difference of (a) spontaneous alpha wave and (b)-(e) fundamental SSVEP from occipital lobe to parietal, central, frontal and frontal pole areas for the same subjects as Fig. 2 (from top to bottom in each array). (a) Spontaneous alpha wave and (b) 5 Hz stimuli (histograms under are illustrated in the next page). The cut-off frequency of the low-pass filter, f_c is 0.5 Hz.

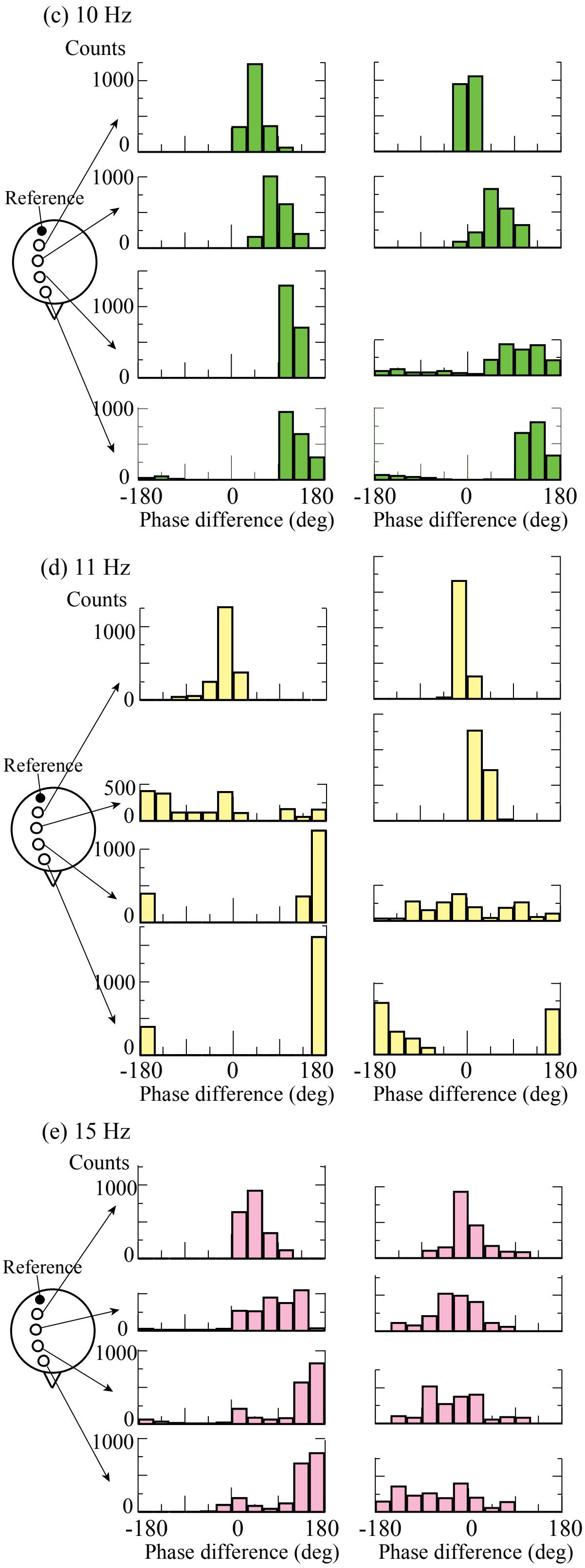

Fig. 3 Histograms of spatial phase difference under (c) 10, (d) 11 and (e) 15 Hz flicker stimuli (continued from the previous page).

The phase difference of the fundamental SSVEP under 5 Hz stimuli bifurcates at the parietal region for subject A; about 60 % of the counts of the phase differences are increased with increasing the distance from the occipital lobe, whereas the rest of the phase differences are decreased. Since the counts of the phase differences between the frontal pole and the occipital area are concentrated from -60 to -90 deg, the phase reversal is not completed. For another subject B, the spatial phase structure is shifted to the standing wave with large phase change between the parietal and central regions.

Both of the histograms for the two subjects clearly show the property of the traveling wave with the phase reversal under 10 Hz stimuli (Fig. 3(c)). The phase differences between the adjacent electrode sites are almost the same from the parietal-occipital phase difference to the frontal pole-frontal phase difference.

In contrast, the phase structure under 11 Hz stimuli is changed to that of the standing wave for both subjects. The phase gap appears in the central region for subject A, while it arises in the frontal region for subject B.

Under the condition of high stimulus frequency, the phase property of the traveling wave can be remarkably seen such as shown in Fig. 3 (e). It is also note that the phase difference is increased with increasing distance from the occipital lobe for subject A, but it is decreased for subject B. Dependence of the advance/retardation on the stimulus frequency is not clarified yet, but it should be further investigated from the viewpoint of the neuronal pathways of the oscillations evoked by the flicker stimuli.

- Second harmonic SSVEP -

Figure 4 depicts the phase difference histograms of the second harmonic SSVEP. The phase difference used in each histogram is based on the estimated phases of the second harmonic SSVEP, the oscillation with of the frequency double of the stimulus frequency.

The phase structure of the second harmonics under 5 Hz has the property of the traveling wave for subject A, whereas the standing wave for subject B. The property of the traveling wave is observed in both histograms under 10 Hz stimuli.

Although each spatial phase property of the second harmonic SSVEP under 5 and 10 Hz stimuli is the same as the property of the fundamental SSVEP under the same stimulus condition, it is not obviously seen the strong correlation between the properties of the fundamental SSVEP and its second harmonics. It should be noted that the amplitude of the second harmonic SSVEP is much smaller than that of the fundamental SSVEP and the estimated phase of the second harmonics is considerably contaminated with noises and artifacts included in the EEG recording.

In fact, under 14 Hz stimuli, the phase difference histograms show neither the standing-wave-like property nor the traveling-wave-like property, which is caused by the low signal to noise ratio of the second harmonic SSVEP over the entire scalp.

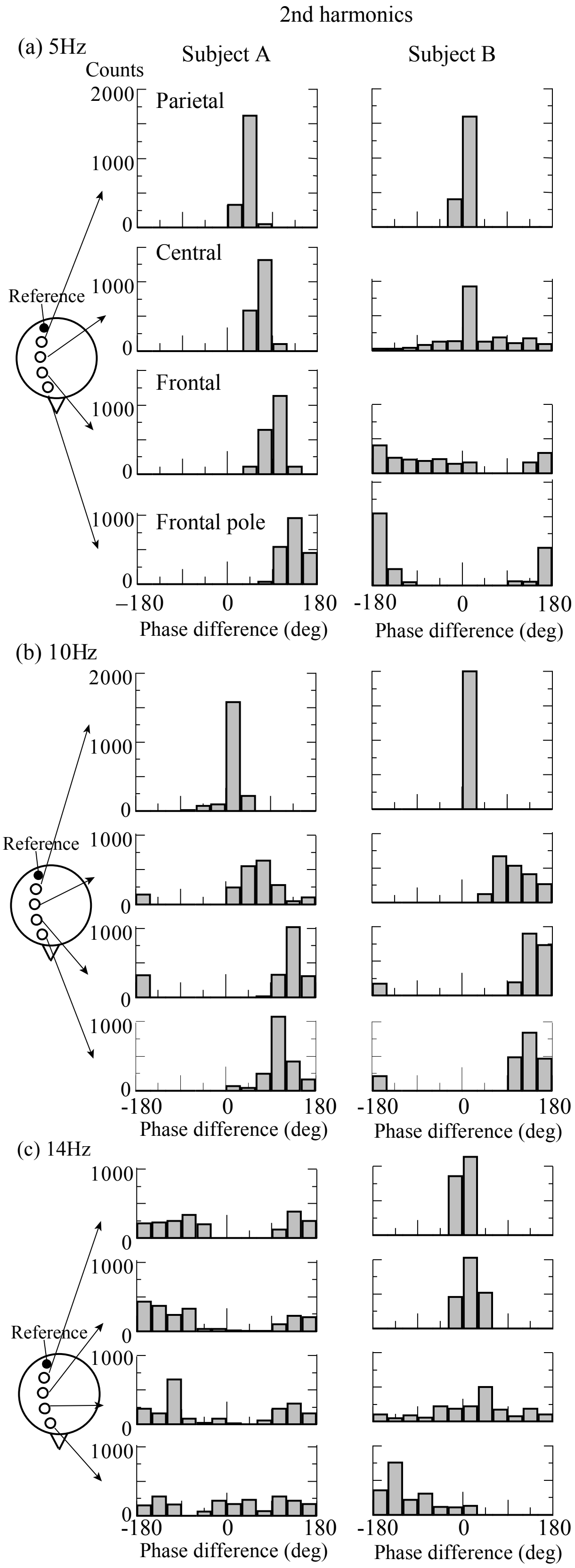

Fig. 4 Histograms of spatial phase difference of the second harmonic SSVEP with reference to occipital lobe, (a) 5, (b) 10 and (c) 14 Hz stimuli, with the same f_c (=0.5 Hz) as Fig. 3.

- Dependence of phase structure on stimulus frequency range -

Since the phase structure seems to be depending on the stimulus frequency, we examine the number of subjects whose SSVEP show the property of the standing wave and traveling wave and other property which belongs neither the standing wave nor traveling wave.

Figure 5 shows the dependence of the number of subjects belonging to each of the three properties on the stimulus frequency range. For simplification, the overall stimulus frequency is divided into three ranges; low frequency range from 5 to 7 Hz, middle range from 8 to 13 Hz, corresponding to the alpha wave, and high range from 14 to 20 Hz.

The two numbers of subjects respectively belonging to the standing wave and traveling wave are comparable in the low and middle frequency ranges. The former is increased by 3 in the high frequency region, whereas the latter is reduced by half. Thus the increase of the stimulus frequency tends to evoke the property of the traveling wave.

On the other hand, the number of subjects having the property of the traveling wave is more than a half of the subjects but decreased considerably decreased in the high frequency region, whereas the number of subjects belonging to the standing wave is invariant over the entire frequency region. The fact the amplitude of the second harmonic SSVEP is very small in this frequency region may cause the decrease the number of subjects belonging the traveling wave.

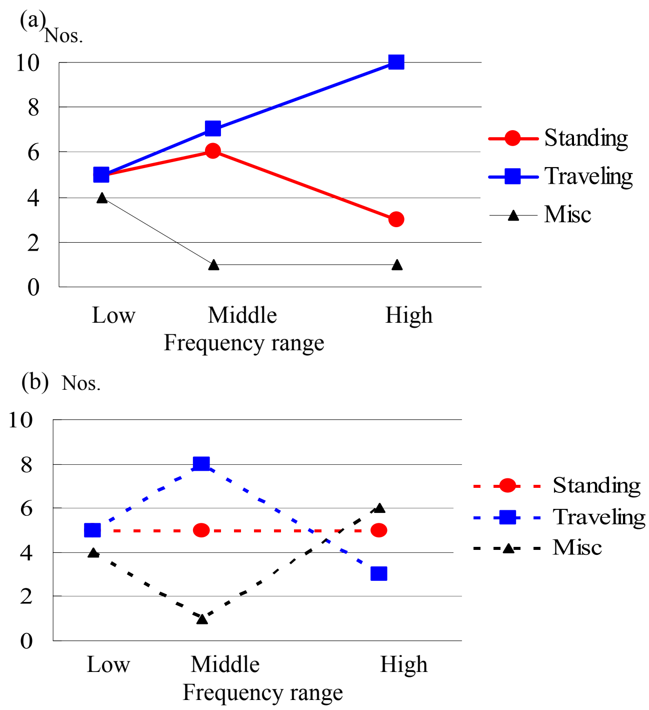

Fig. 5 Dependence of phase structure on stimulus frequency range. (a) fundamental SSVEP and (b) its second harmonics.

- Relationship between phase structure and amplitude distribution -

Figure 6 shows the representative examples of the amplitude distribution and phase difference structure. In Fig. 6(a), the amplitude spectrum is seen to have a sharp and large peak at the stimulus frequency f_{stim} in each spectral distribution, which is accompanied by the phase structure of the traveling wave. Such relationship is observed in about 60 % of the cases in which the amplitude of the SSVEP is dominantly large in each spectral distribution from the frontal pole to the occipital lobe. It is plausible that the SSVEP is elicited and intensively driven to establish the strong correlation over the entire scalp by flicker stimuli.

The property similar to the traveling wave is also seen in the phase structure of the SSVEP in which the spectral amplitude at f_{stim} is very small in the anterior region (frontal lobe and frontal pole) (Fig. 6(b)). The traveling-wave-like structure is seen in about 45 % of all the cases in which the SSVEP amplitude in the frontal region is much smaller than that in the occipital region, whereas about 25 % of all the cases show the standing-wave-like property. Excitability of the SSVEP should be rather weaker than the above and locally driven oscillatory activity in the posterior region may be transmitted toward the anterior region.

The standing-wave-like phase structure is mostly seen in the case for which the spectral amplitude in the central region is much smaller than that in the frontal and central lobes as shown in Fig. 6(c). About 45 % of such spectral distributions correspond to the phase gap of the standing-wave-like phenomenon. It is possible that the SSVEPs elicited in the occipital and frontal region travel and competitively interact with each other in the central region. Such antagonism may cause the amplitude blocking and phase disordering of the SSVEP in the central region.

- Correlation between SSVEP and alpha wave in terms of phase structure -

The spatial phase structure of the SSVEP is compared with that of the spontaneous alpha wave in order to investigate the effect of the alpha wave on the SSVEP. In particular, the entrainment of the alpha wave is considered to affect the fundamental SSVEP under the condition of the middle stimulus frequency range (8 -13 Hz) and the second harmonics under the condition of the low stimulus frequency range (5 – 7 Hz). The present study adopts the spatial phase structure of the SSVEP which is mostly observed in all of the stimulus frequencies as the representative of the spatial phase structure of the SSVEP for each subject.

The number of subjects whose fundamental SSVEP have the same representative phase structure as the spontaneous alpha wave is 10 of 14, whereas 3 for the second harmonic SSVEP. In addition, the number of subjects whose alpha wave under the flicker stimuli show the same phase structure as the spontaneous alpha wave is 10 of 14.

Thus there is a possibility that the fundamental SSVEP is rather affected by the spontaneous alpha wave or the underlying mechanisms of the two rhythms are similar to each other. Although the correlation between the second harmonics and the spontaneous alpha wave is weak in terms of the phase structure, note that the weak response of the fundamental SSVEP makes it difficult to determine the representative phase structure.

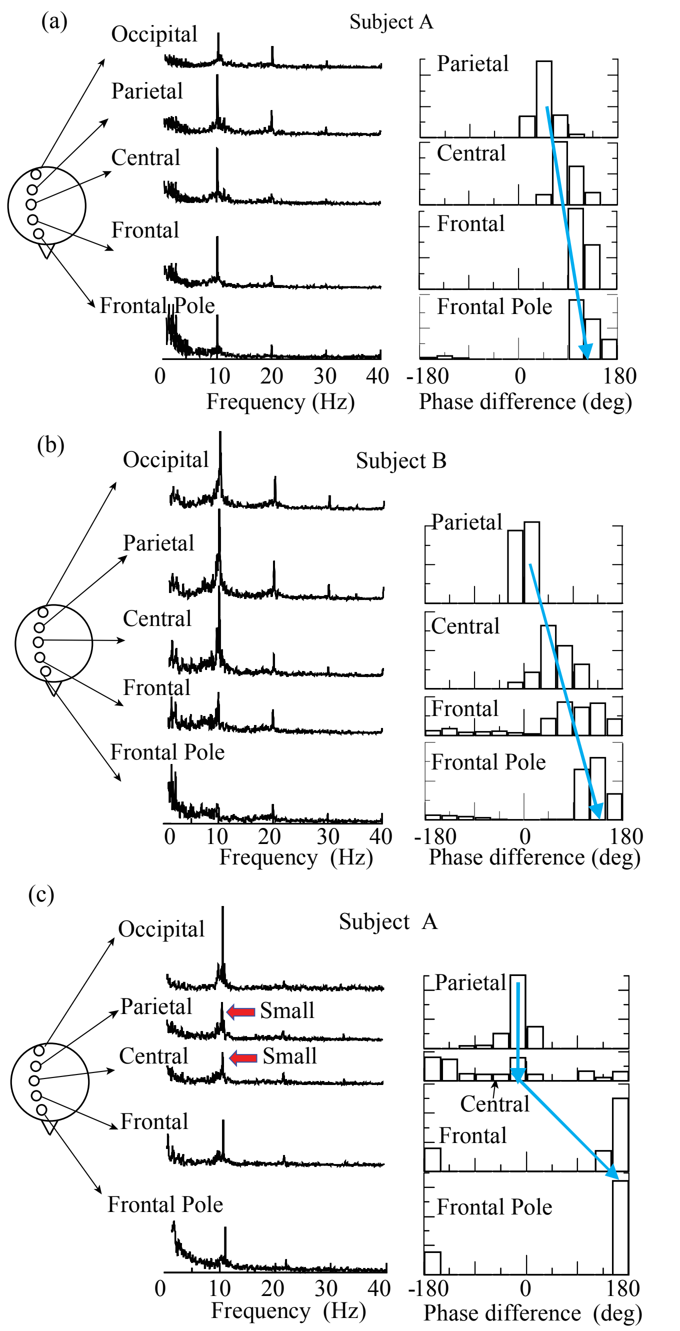

Fig. 6 Power spectrum of the EEG from occipital to frontal regions and histograms of phase difference with reference to occipital lobe. Examples of traveling-wave-like property under 10 Hz stimuli for (a) subject A and (b) subject B and an example of standing-wave-like property under 11 Hz stimuli for subject B.

Some researchers have tried to explain why the spatial structure of the SSVEP differs dependently on individuals and stimulus patterns (unstructured flicker and checkerboard); e.g., Silberstein et al. have proposed that the phase structure depends on the strength of mutual interference of elicited activities in various regions of the brain where visual information given by the flicker stimuli are projected via the complicated visual pathways. Strong interference generated from global oscillatory activities elicited by the flicker stimuli yields the phase gap corresponding to the standing wave, whereas weak interference from local activities elicited by the checkerboard does not [6,7].

Observations obtained from the amplitude spectra and the phase structure in this study also suggest that the spatial phase structure of the fundamental SSVEP depends on the amplitude of the SSVEP which reflects the elicitation intensity of the flicker stimuli. Moreover, the present study indicates that the phase structure depends on the stimulus frequency as well as the individuals and stimulus spatial patterns.

In particular, the increase of the subjects showing traveling-wave-like property suggests the possibility that not only the sensitivity of neuronal activities to flicker stimuli decreased with increasing the stimulus frequency but also the elicitation is localized as shown in Fig .6(c).

The striking high correlation between the fundamental SSVEP and the spontaneous alpha wave is shown in terms of the phase structure. The relationship between the two rhythms has not been well elucidated qualitatively and quantitatively. Further investigation is needed to clarify the underlying mechanisms of the two rhythms.

4. CONCLUSION

This study has investigated the spatial phase structure of the fundamental SSVEP and the second harmonic SSVEP under the flicker stimuli. The phase structure of the fundamental SSVEP depends on the stimulus frequency as well as the individuals. The spatial phase structure of the fundamental SSVEP mainly depends on individuals under the condition of the low and middle stimulus frequency range, but the traveling-wave-like SSVEP becomes dominant under condition of the high stimulus frequency range. The phase structure of the fundamental SSVEP is remarkably correlated with that of the spontaneous alpha wave. Dependence of the phase structure on the stimulus frequency should be investigated quantitatively from the clinical viewpoint such as diagnosis of photosensitive epilepsy as well as from the fundamental study of the underlying mechanisms of the SSVEP and the alpha wave.

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