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Difference of EEG dynamics when listening to comfortable or uncomfortable sound

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Abstract— In this study, we examined the difference of EEG patterns when subjects are listening to comfortable or uncomfortable sound. EEG waves were measured at four positions (FP1, FP2, P3, P4). Two kinds of sounds, which are comfortable or uncomfortable to most of us, were provided to the subjects. Consequently, we found that the shapes of the cross-correlation of FP1 and FP2 EEG waves are different. The cross-correlation in response to comfortable sound decays 250[ms] faster on average than that to uncomfortable sound, and the gradient of the cross-correlation of comfortable sound is 53.7% larger than that of uncomfortable one. This result suggests that the speed of information transmission in the prefrontal cortex may depend on whether the emotional impression is comfortable or uncomfortable, while it does not depend on dynamical dimension or difference of frequency component.

1. Introduction

In physiopsychology of recent years, it is an interesting theme to identify the part where EEG waves are very active with the mental action, especially the emotion [1]. Heller proposed the two dimensional model, in which pleasure or displeasure can be measured with the difference of right and left frontal region and that the arousal level is measured in the right parietal region [2].

However, it is still unclear because there are a lot of discussions for the element of emotion. Concerning the feeling of anxiety, for example, some studies reported no difference between the hemispheres [3], others insisted that the right or the left hemisphere is involved with it [4][5]. On the other hand, there are few studies analyzing the temporal difference of EEG waves. Thus, we aim to elucidate not only the activated region but also temporal difference of EEG waves.

For that purpose, we examined the frequency distribution by FFT (Fast Fourier Transform) and the cross-correlation of EEG waves when a subject is listening to a comfortable or an uncomfortable sound. We focused on the quantitative relation of α wave (8-13Hz), β1 wave (13-20Hz), and β2 wave (over 20[Hz]) in the measurement region, and the cross-correlations of four pairs (FP1/FP2, FP1/P3, FP2/P4, P3/P4) to see the temporal relation of the EEG waves. In addition, we analyzed the correlation dimension of the attractors of brain waves.

We could not find any difference in the power spectrum of α and β waves. However, we found that the shapes of the cross-correlation of FP1 and FP2 EEG waves are different. The correlation of FP1 and FP2 in response to comfortable sound decays 250[ms] faster on average than that to uncomfortable sound, and the gradient of the cross-correlation of comfortable sound is 53.7% larger than that of uncomfortable one. This result suggests that the speed of information transmission in the prefrontal cortex may depend on whether the emotional impression is comfortable or uncomfortable.

2. Experiment of electroencephalogram

Subjects listened to comfortable and uncomfortable sounds (20[s] silence + 20[s] a comfortable or an uncomfortable stimulus sound + 20[s] silence). EEG waves during their listening were measured and analyzed.

2.1. Stimulus sound

First of all, the stimulation sounds of the comfortable and the uncomfortable were selected as follows. We prepared 30 kinds of sounds. The sample sounds are selected from environmental sound CD, created from MIDI sound, and synthesized speech sounds. And, they have been adjusted to the full length of 20[s].

Twelve men from 18 to 24 years old who do not belong to the subjects of our experiment evaluated the sounds by seven levels of comfort. The levels are as follows: 1 → fairly, 2 →considerably, 3 → very. We defined comfortable as + (plus), uncomfortable as - (minus). If it is neither comfortable nor uncomfortable, they should evaluate it as 0 (zero). In addition, the average scores for each sample sound are calculated from the evaluations of the questionnaires. The highest score of them all was selected as a comfortable sound, and the lowest score was selected as an uncomfortable one. Table 1 shows the average scores for each sound. Thus, #25 was selected as a comfortable sound, and #03 was selected as an uncomfortable sound.

Table 1: Results of the Questionnaire

Sound #	Ave. Scores	Sound #	Ave. Scores
01	-0.3	16	+0.5
02	-0.6	17	+0.6
03	-2.2	18	-2.1
04	+1.5	19	-0.4
05	+0.3	20	-1.8
06	+0.9	21	-0.4
07	+0.2	22	+1.7
08	-0.9	23	+0.8
09	0	24	+1.2
10	-0.7	25	+1.9
11	-0.8	26	-0.9
12	+0.7	27	+0.3
13	-0.5	28	-0.5
14	-0.2	29	-0.7
15	+1.8	30	-1.3

2.2. Method of measurement

In this experiment, four positions of frontal pole (FP1, FP2) and parietal region (P3, P4) were measured by the reference recording method. In the reference recording method, both auricular positions are short-circuited as a reference electrode. This method has the effect of suppressing the influence of the electrocardiogram and the electromyogram on an auricular position. This is suited to examine the correlation between right and left positions in this experiment.

The measurement system is constructed as follows. Each subject sits relaxed on a chair in the electrostatic shield which is grounded. Brain wave signals are transmitted to the amplifier through an input box. They are amplified 10^5 times and transmitted to a personal computer via an analog-digital converter. We set the parameters of the amplifier as follows: LOW CUT=0.5[Hz], HIGH CUT=300[Hz], and HUM FILTER="ON" to remove alternating-current interference. The sampling frequency is set to 1024 ($= 2^{10}$)[Hz] to see the frequency distribution by FFT (Fast Fourier Transform) [7]. As a power supply, we use an isolation transformer for safety and noise reduction. Each one of 12 subjects (gender:male, age:21 – 28) sat on the chair with closed eyes, the electrode attached in the measurement positions, and the headphone loaded in the measurement box. Encapsulated type headphone was used to raise the soundproofing.

The length of a comfortable and an uncomfortable sound is 20[s] each. Each stimulation (comfortable / uncomfortable) is given only once for each subject. All of the stimulus sounds are monophonic.

3. Analytical methods and results

3.1. Frequency analyses

In this section, we focus on the modification of activated region and the difference of brain wave distribution at stimulation (comfortable / uncomfortable). Figure 1 - 2 show the magnitude of the α waves during the stimulus period at the measurement positions of all subjects. Whether the stimulus is comfortable or uncomfortable is indicated in the parentheses of the caption.

There is no quantitative difference at the α wave by the difference of stimulation between the measurement positions. When the subjects are different, it turned out that the activated positions were different even if the stimulation is the same (see Figure 1 - 2).

Consequently, we found no quantitative difference between the measurement positions of the α wave by the difference of stimulation. In addition, the $\beta 1$ and the $\beta 2$ waves were almost the same results as those of α wave. Therefore, the result of the α wave is only shown below in this paper.

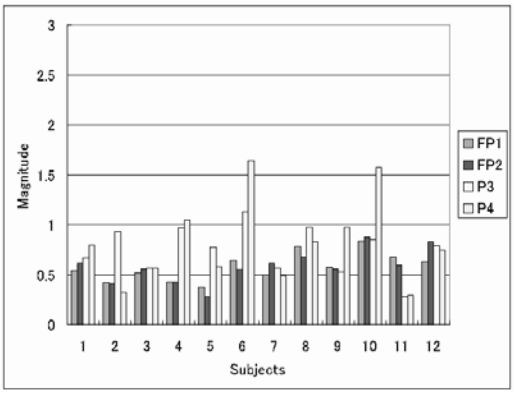

Figure 1: α wave (comfortable sound)

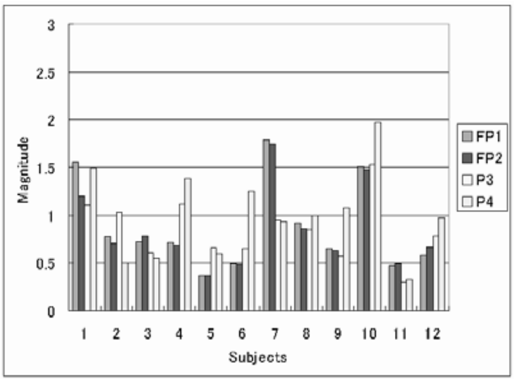

Figure 2: α wave (uncomfortable sound)

3.2. Cross-correlation

The cross-correlations of EEG waves are calculated from two positions. Since we measure four positions, the combination of pairs is as follows: (FP1/FP2, FP1/P3, FP2/P4, P3/P4). The cross-correlation is calculated as follows:

$$R(k) = \frac{1}{N-k} \sum_{n=0}^{N-k-1} x(n+k) \cdot y(n), \tag{1}$$

where k $(= 0, 1, 2, \cdots, N-1)$ is the temporal shift, $x(n)$ and $y(n)$ are the magnitudes of the EEG waves at time $= n$, and N is the period of the data. For normalization of the cross-correlation, we divide R(k) by the maximum value of R(k) as follows:

$$C(k) = \frac{R(k)}{R_{max}}, \tag{2}$$

where k is the same variable in equation (1), and R_{max} is the maximum value of R(k). A typical example of the cross-correlations obtained through this procedure is shown in Figure 3. The three lines correspond to those in response to three kinds of stimulus (comfortable / uncomfortable / non-stimulus) through $k = 4000$[ms]. Figure 3 suggests that the speed of decay of the cross-correlation curve (FP1/FP2) is different, depending on each stimulus (comfortable / uncomfortable / non-stimulus). To examine this property more quantitatively, we estimate the gradient of the cross-correlation curve under the following conditions.

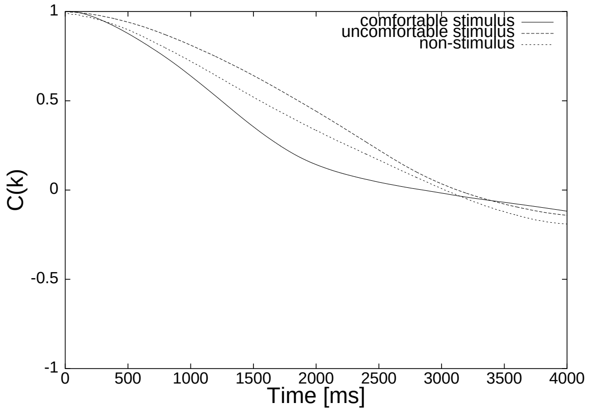

Figure 3: An example of cross-correlation of FP1/FP2

1. "Linear line" whose length should be more than or equal to 400[ms].
2. The χ^2 value [6] of the "linear line" should be more than 0.99.

Under these conditions, we searched for a linear part from the graph of the cross-correlation. And we calculated the start time of decreasing and the magnitude of the gradient of the approximated linear line. Figure 4 shows that the mean gradient for each stimulation (comfortable / uncomfortable). The gradient in response to a comfortable sound is larger than that to an uncomfortable sound. And Table 2 shows that the start times of linear decrease of the cross-correlation curves. When the positive value is larger, the cross-correlation to a comfortable sound begins to decay earlier. These properties are the case in FP1/FP2 only, but not in the other pairs (FP1/P3, FP2/P4, P3/P4). The result of Table 2 is based on the data of nine subjects except three samples whose cross-correlation was much affected by noises. Consequentially, the cross-correlations of prefrontal EEGs in response to a comfortable sound decays 250[ms] faster on average than that to an uncomfortable one, and the magnitude of the gradient of a comfortable sound was 53.7% larger than that of an uncomfortable one.

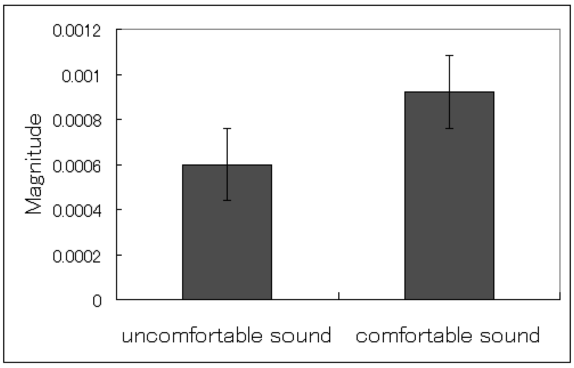

Figure 4: Magnitude of gradient of cross-correlation
bar : standard error of the mean

Table 2: The time of decrease of the cross-correlation

Subjects number	Time to fall [ms]
01	50
02	100
03	450
04	500
05	0
06	300
07	200
08	500
09	150

3.3. Correlation dimension

In the FP1 and FP2, we analyzed the correlation dimension. First of all, we reconstructed the attractor by delayed time τ in m dimension space from the measurement data. Generally, the time τ is set to the time (for example $\tau = 2621$) where the auto-correlation is almost zero. Since we did not get enough embedded dimension under such τ, we set τ to 500, where the auto-correlation is small enough.

Secondly, the correlation dimension, that is one of the scale of the fractal dimensions, is calculated through the correlation integral for the attractor:

$$C^m(r) = \lim_{N\to\infty} \frac{1}{N^2} \sum_{i,j=1,i\neq j}^{N} H\,(r - |X_i - X_j|), \qquad (3)$$

where $X_{i,j}$ $(i, j = 1, 2, \cdots, N)$ $(i \neq j)$ is a point on attractor in m dimension space, r is the radius of m dimensional hypersphere, and H is the Heaviside function. If the correlation integral is represented by the equation (4), $\nu(m)$ is called a correlation exponent.

$$C^m(r) \propto r^{\nu(m)} \qquad (4)$$

The saturated value of $\nu(m)$ is the correlation dimension with increasing embedded dimension. Table 3 shows that correlation dimension of five subjects during the stimulus anterior half period (10[s]) in FP1 or FP2. We were not able to find a general relation between the stimulation and the correlation dimension from these results.

In previous studies, the correlation dimension of EEG in doing a task tends to be higher than that in no task [7][8]. Therefore, we expected that the correlation dimension of uncomfortable sound is higher than that of comfortable one. However, such a tendency was not found in our experiment.

Table 3: Correlation dimension

Subject number	sound 1		sound 2	
	FP1	FP2	FP1	FP2
01	4.9	4.1	4.3	4.0
02	1.5	1.2	1.4	1.2
03	1.2	1.3	3.9	4.1
04	3.2	1.2	2.9	3.0
05	2.3	1.6	2.0	0.8

sound 1 = uncomfortable sound
sound 2 = comfortable sound

4. Conclusions

The cross-correlations of prefrontal EEGs in response to a comfortable sound decays 250[ms] faster on average than that to an uncomfortable one, and the gradient of a comfortable sound was 53.7% larger than that of an uncomfortable one. We found no quantitative tendency among the strengths of the α and β waves and no tendency common to correlation dimensions. The stimulus sounds used in this experiment are monophonic sounds. Thus, there will be little difference in the responsive activity of the right and the left hemisphere by the stimulus in itself. Our results suggest that the speed of information transmission in the prefrontal cortex may depend on whether the emotional impression is comfortable or uncomfortable, while it does not depend on dynamical dimension or difference of frequency component.

The study of the dynamics behind the curve of cross-correlations is one of our future works. Moreover, whether the cross-correlation of EEG can be an indicator for emotional responses in other stimuli will be an interesting research topic.

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