On the Largest Lyapunov Exponents of Finger Plethysmogram and Heart Rate under Anxiety, Fear, and Relief States

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Abstract—**We investigated the largest Lyapunov exponents (LLEs) of finger plethysmogram (FPG) and heart rate (HR) under anxiety, fear and relief states and compared each measured LLEs with the HR. We devised a task in which the participants experienced the emotions of anxiety, fear, and relief. FPG and HR were recorded during the task, and chaos analysis was applied to FPG to calculate the LLEs. Our results showed significant positive correlations between the LLEs of FPG and the degrees of anxiety and fear. In addition, the degree of relief showed a significant negative correlation with the LLEs of FPG. However, no significant correlation was observed between HR and the degrees of three emotions. These results suggest that the LLEs of FPG are a more sensitive psychological index than the HR.**

I. INTRODUCTION

SINCE it was discovered that a finger plethysmogram (FPG) shows chaotic fluctuations, several researchers have attempted to assess human psychophysiological states using a chaos analysis to the signals the organism emits [1]-[4][1]. The chaos analysis is used to evaluate the chaotic fluctuation, which is expressed by the largest Lyapunov exponents (LLEs). Although numerous studies have performed the chaos analysis of FPG to predict human psychophysiological states, none have attempted to verify how a changing psychological state influences chaotic fluctuations (LLEs); thus, the relation between the FPG and the LLEs in this context has not been fully examined.

The purpose of the present study was to investigate the LLEs of FPG and the heart rate (HR) during states of anxiety, fear, and relief, and to clarify the relation between FPG and the LLEs obtained in these states.

II. METHOD

A. Participants and Experimental Conditions

The participants were 24 university students (12 males and 12 females, mean age: 21.9).

The experiment was performed in a soundproofed and shielded experimental booth. Temperature was held constant at 24 to 25℃.

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[1] Studies using chaos analysis of finger plethysmogram have only been conducted in Japan.

B. Stimulus

The stimulus was presented by Microsoft Office PowerPoint2003 (see Fig.1). As shown in Fig.1, the stimulus had a shape of reversed "T". The background was black and the lighting point was red. The lighting point moved every three seconds from (A) to (B), then (B) to (C), or (D). The sign, "Shock!?" or "Non-Shock!!", was presented at (C) or (D). The period of (A) to (B) was termed the vertical period, and that of (B) to (C) or (B) to (D) is called the horizontal period.

C. Task

The task in this experiment was based on that devised in a previous study [5]. When the lighting point moved to the sign, "Shock!?," the participant might be given an electric shock, and when the lighting point moved to the sign, "Non-Shock!!," they were not shocked. The previous study showed that this task induced the feelings of anxiety, fear, and relief [5].

In the previous study, the electric shock was used as an aversive stimulus. In this experiment, however, the participants were not given electric shocks, although they were told to be shocked. Thus, the experimenter was carried out, giving a false instruction about electric shocks [6].

D. Experimental Conditions

In this experiment, three experimental conditions, as shown in Fig.2 and 3, were set up.

1) Shock Condition: When the signs, "Shock!?" and "Non-Shock!!," were presented at (C) or (D) of Fig.1, the lighting point moved to "Shock!?" (see Fig.2).

2) Non-Shock Condition: When the signs, "Shock!?" and "Non-Shock!!," were presented in (C) or (D) of Fig.1, the lighting point moved to "Non-Shock!!" (see Fig.2).

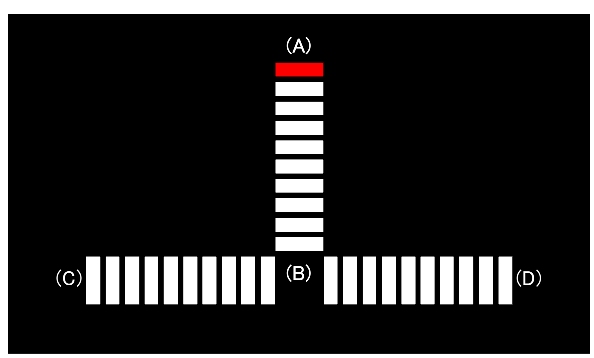

Fig. 1. The Stimulus in This Experiment.

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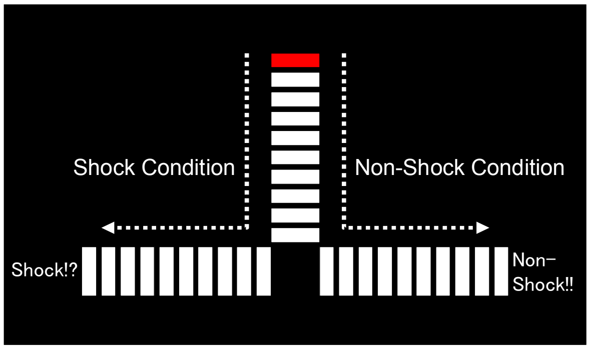

Fig.2. The Stimulus under the Shock Condition and the Non-Shock Condition.

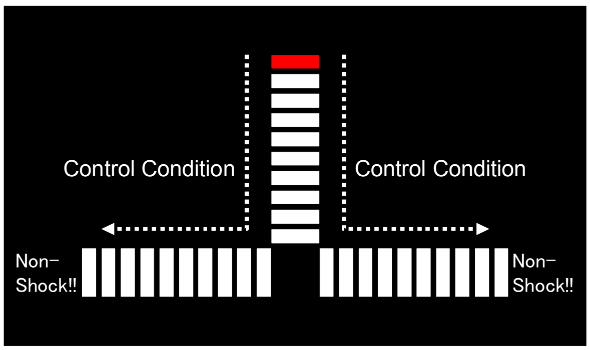

Fig.3. The Stimulus under the Control Condition.

3) Control Condition: Signs stating, “Non-Shock!!,” were presented at both (C) and (D) in Fig.1 (see Fig.3).

Under the shock condition or the non-shock condition, the participants could not predict the experimental condition while in the vertical period but could estimate it in the horizontal period. Under the control condition, however, the participants could immediately predict the experimental condition after starting the experimental task because the “Non-Shock!!” signs at (C) and (D) were presented.

E. Physiological Measurements

FPG and electrocardiogram (ECG) were recorded. FPG was measured using BCU101 (CCI Inc.) and recorded by a personal computer. The sampling rate was 200Hz and the time constant, one second.

ECG was measured by ML132 (ID Instruments) and recorded by a personal computer. The sampling rate was 1,000Hz. The high cut- and low cut- frequencies were 100Hz and one Hz, respectively.

F. Procedure

This experimental design and procedure conformed to the Code of Ethics of Kwansei Gakuin University, Japan.

Each participant was seated in the experimental booth and given an explanation regarding the experiment. However, the experimenter did not provide details in order to avoid negative feelings such as anxiety or fear that might disturb the experimental operation. Participants wore a FPG sensor and disposable ECG electrodes and rested quietly for five minutes.

The experimenter gave the instructions concerning the task to the participant and carried out a practice session in which each experimental condition was run in turn. After that, the electrodes were attached to the participants.

Then, main trials were carried out. Fig.4 shows one of the trial in this task. First, a sign stating, “The task will soon start, so please wait,” was presented for 30 seconds, and the participant rested quietly in the “Pre- Task Period.” Second, 10 seconds were counted down. Third, the stimulus was shown with the vertical and the horizontal periods, each lasting 30 seconds. Fourth, the blank stimulus was presented for five seconds. Fifth, a sign stating, “The task will soon finish, so please wait,” was presented for 30 seconds and the participant rested quietly again. This was the “Post- Task Period.”

The place of the sign stating, “Shock!?” or “Non-Shock!!,” and the direction in which the lighting point moved were determined at random. Physiological measurements were recorded over four testing periods.

The three trials were carried out under each experimental condition one by one. However, the experimenter instructed the participants that six trials would be performed so that participants would not predict the experimental condition of the next trial. Then, a two minutes interval was imposed between the trials. After three trials, in order to get “Affective Scores,” each participant estimated the degree of anxiety, fear, and relief during each period in all the trials.

The total time for this experiment was about 50 minutes.

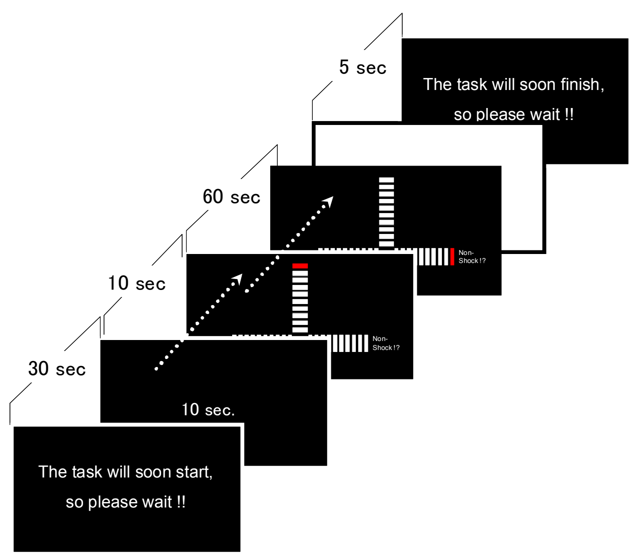

Fig.4. An Example Trial in This Task.

G. Data Analysis

1) Attractor: Fig.5 shows the flowchart from the FPG measurement to the reconstruction of the attractor. For the time series data $x(i)$, with i=1,…, N, obtained from the FPG, the phase space was reconstructed using the method of time delays. Assuming that we create a d-dimensional phase space using a constant delay τ, the vectors in the space are generated as d-tuple from the time series and are given by

$$\mathbf{X}(i) = (x(i),...,x(i-(d-1)\tau)) = \{x_k(i)\} \qquad (1)$$

where $x_k(i) = x(i-(k-1)\tau)$, with k=1,...,d. In order to reconstruct the phase space correctly, the parameters of the delay τ and the embedding dimensions, d, should be chosen optimally [7]. For the time series recorded from the FPG, we chose the parameters τ=50 ms and d=4 [1] [2].

2) The LLEs: In the reconstructed phase space, one of the most important measures of complexity consists of the LLEs, λ_1. Consider $\mathbf{X}(t)$, the evolution of some initial trajectory $\mathbf{X}(0)$ in the phase space over time, given by

$$\lambda_1 = \lim_{t\to\infty}\lim_{\varepsilon\to 0}\frac{1}{t}\ln\frac{|\delta\mathbf{X}_\varepsilon(t)|}{|\varepsilon|} \qquad (2)$$

where

$$\delta\mathbf{X}_\varepsilon(t) = \mathbf{X}(t) - \mathbf{X}_\varepsilon(t)$$
$$\varepsilon = \mathbf{X}(0) - \mathbf{X}_\varepsilon(0)$$

for almost all initial difference vectors $\varepsilon = \mathbf{X}(0) - \mathbf{X}_\varepsilon(0)$. We estimated λ_1 using the algorithm of Sano and Sawada [9]. λ_1 describes the divergence and instability of the orbits in the phase space.

The LLEs, λ_1, were calculated for a basic window of 6,000 points.

Fig.6 shows the flowchart from the FPG measurement to the calculation of the LLEs.

We prepared the attractors for four embedding dimensions from pulse wave data with chaotic characteristics and calculated the largest Lyapunov exponents, which reflect the divergence of the attractor trajectory [9].

3) Mean Scores: The obtained FPG of LLEs, HR and affective score for the four periods were used to calculate mean scores.

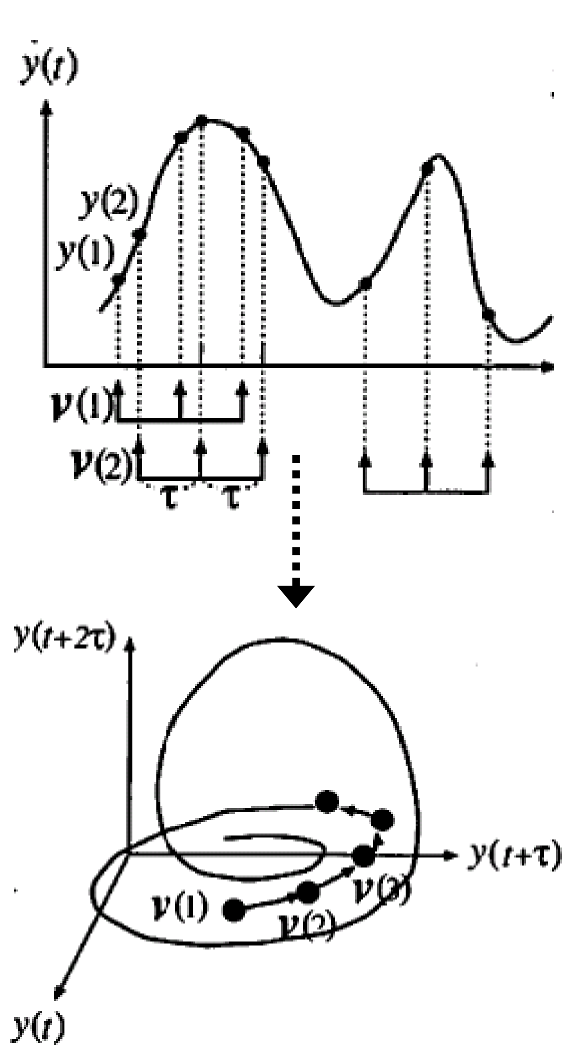

Fig.5. The Flowchart from the FPG Measurement to the Reconstruction of the Attractor [8].

H. Data Reduction

Because one participant did not believe the false instructions, his data were eliminated. The obtained data from 23 participants (11 males and 12 females) were analysed.

III. RESULTS

A. Correlation Coefficient between Physiological Measurements and Affective Scores

Table I shows the correlation coefficient between physiological measurements and affective scores. No significant correlations were proved between HR and affective scores. However, significant positive correlations between the LLEs and affective scores were found.

B. The Relation between Shape of the FPG and LLEs

Fig.6 presents a sample of FPG during the task under the shock condition. The FPG in the vertical period slightly changed, but the FPG in the horizontal period changed in amplitude and baseline deflection much more than the former. This change indicates that anxiety and fear were induced in the participants. During the horizontal period under the shock condition, the participant might anticipate that the electric shock would be given later.

Fig.7 and 8 show the attractors of the vertical and horizontal periods in Fig.6, respectively. In the vertical period, the attractor had a comparatively periodic trajectory. However, in the horizontal period, it deviated from a periodic trajectory.

The LLEs in the vertical and horizontal periods were 2.50 and 7.18, respectively, clearly demonstrating that the LLEs were much higher in the horizontal period.

TABLE I
Correlation Coefficient between Physiological Measures and Affective Scores.

N = 12		LLE	HR	Anxiety	Fear	Relief
Physiological Measurements	LLE	–	.53	.76 **	.74 *	−.85 **
	HR		–	.14	.11	−.52
Affective Scores	Anxiety			–	.98 **	−.86 **
	Fear				–	−.85 **
	Relief					–

**p <.001; *p <.01

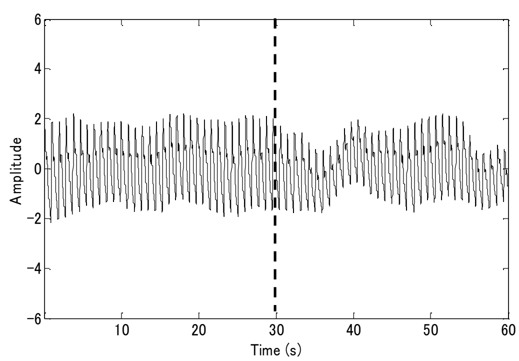

Fig.6. The Sample of FPG during the Task under the Shock Condition.

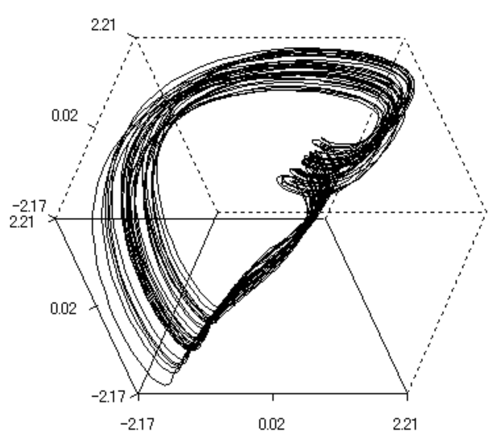

Fig. 7. The Attractors of the Vertical Period in Fig.6.

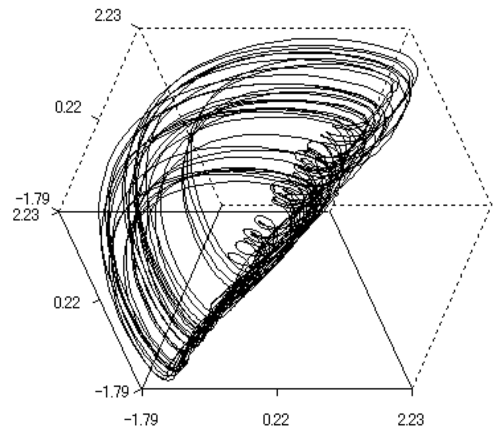

Fig. 8. The Attractors of the Horizontal Period in Fig.6.

IV. DISCUSSION

Significant positive correlations were observed between the LLEs of FPG and degrees of anxiety and fear. Additionally, the degree of relief showed a significant negative correlation with the LLEs of FPG. However, no significant correlation was found between HR and the degree of the three emotions. In a previous study, when fear was induced in the participant, the HR increased [5]. The present study was not able to replicate it. Our results suggest that the LLEs of FPG are more sensitive psychological index than the HR.

We hypothesized that the LLEs of FPG show the arousal level or tension because the LLEs of FPG were high and corresponded to the degree of anxiety and fear. For example, during driving a car, the LLEs of FPG are higher on a curved road than on a straight one [10]. Practically speaking, this means that we need to heighten our arousal level and degree of tension when driving on a curved road and should not drive in a sleepy state.

We were unable to confirm the aforementioned hypothesis because experimental procedure was insufficient to verify it. In the future, we will re-evaluate our procedures and carry out further experiments to defend the hypothesis.

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