Relationship between Emotional State and Pupil Diameter Variability under Various Types of Workload Stress

Kiyomi Sakamoto[1], Shoichi Aoyama[1], Shigeo Asahara[1], Haruki Mizushina [2], and Hirohiko Kaneko[2]

[1] Corporate R&D Strategy Office, Panasonic Corporation,
3-1-1 Yagumo-naka-machi, Moriguchi City, Osaka 570-8501, Japan
Tel: +81-6-6906-0718, Fax: +81-6-6906-1662
{sakamoto.kiyomi, aoyama.shoichi, asahara.shigeo}@jp.panasonic.com
[2] Department of Information Processing, Tokyo Institute of Technology,
4259-G2-3, Nagatsuta, Midori-ku,Yokohama-city, Kanagawa, 226-8502 Japan
Tel.: +81-45-924-5292, Fax: +81-45-924-5293
{mizushina,kaneko }@ ip.titech.ac.jp

Abstract. We carried out two experiments to explore the relationship between the frequency characteristic of pupil diameter variability and emotional state under various types of workload. The workload required the subjects to listen to spoken words and categorize them. The difficulty of the task was adjusted by changing the time interval of the stimulus presentation in Experiment 1 (time-based task) and the number of categories in Experiment 2 (cognitive-based task). Pupil diameter was monitored and recorded using an infrared video camera while observers were performing the tasks. In both experiments, a significant correlation was observed between the frequency characteristic of pupil diameter variability and emotional state. Our results indicated the frequency characteristic of pupil diameter variability to be a potentially useful index for evaluating mental stress.

Keywords: Pupil diameter, audio stimuli, psychological state, variability in pupil diameter

1 Introduction

Technological progress in computer and information systems is delivering higher system performance and an increasing range of functions, but on the other hand, their growing complexity causes increased mental stress during use. Further development of these systems will require an easy-to-use human-machine interface (HMI) to be developed. Measurement of mental stress will be an essential element of this process. Current methods of evaluating mental stress depend chiefly on subjective responses, in spite of these responses often showing considerable variation among individuals. Thus, an objective measurement method of mental stress is needed to improve the accuracy and usefulness of evaluations of HMI.

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Previous studies of objective estimation of users' psychological state have utilized physiological indices, including heart rate (HR) variability, brain waves, and galvanic skin response (GSR). However, wearing the various electrodes and sensors needed for measuring these vital signs may be stressful in itself. One solution to reducing user stress during measurements may be to monitor pupil diameter (PD) using a remote infrared video camera. Pupil diameter is controlled by the autonomic nerve system, as is the heartbeat; and it has been shown that in humans, patterns of change in pupil diameter are closely related to psychological state, especially mental stress. In this study, we explored the relationship between emotional state and pupil diameter variability under various types of workloads using a remote video camera. We also attempted to explore the relationship between heart rate (HR) variability and pupil diameter (PD) variability to confirm the validity of using PD variability as an evaluation index of psychological stress.

2 Experiment 1: Task with Time Pressure

In Experiment 1, pupil diameter (PD) and heart rate (HR) were monitored while the subjects performed the categorizing tasks following the audio stimuli presented at different time intervals. These stimuli induced different levels of psychological stress in the subjects.

2.1 Methods

Subjects: Six adults aged from their 20s to 50s participated in this experiment.

Measurements: The following items were measured as indices of the psychological stress experienced by the subjects: the subjective evaluation of psychological state through interviews, the pupil diameter (PD) as monitored by an infrared video camera, and the heart rate monitored by an electrocardiogram (ECG). Heart rate (HR) variability was obtained from a time series of R-R intervals. In this study, we adopted LF/HF ratios of PD and HR variabilities as indices of frequency characteristics. LF/HF was defined by the power ratio of the low frequency band (LF: 0.04–0.15 Hz) to that of the high frequency band (HF: 0.15–0.5 Hz), calculated by employing FFT analysis [1] [2]. It was assumed that the LF/HF of PD variability might reflect the level of sympathetic nerve activity in the same way as does the LF/HF of HR variability.

Apparatus: Subjects sat in a chair and performed tasks in a dark room. The subjects had to fixate steadily at a point presented on the screen, and their pupil diameter was monitored and recorded by eye movement measurement equipment comprising an infrared video camera (Arrington Research, ViewPoint EyeTracker, Sampling rate 60 Hz). To measure the pupil diameter precisely, the head of the subject was anchored with a head and chin rest. Auditory stimuli were generated by a PC (Apple, MacBook) and presentation software (Cedrus Corporation, SuperLab 4.0) and presented via noise canceling headphones (Bose). Subjects responded to the task using a keyboard (Cedrus Corporation, RB-530 Response Pad).

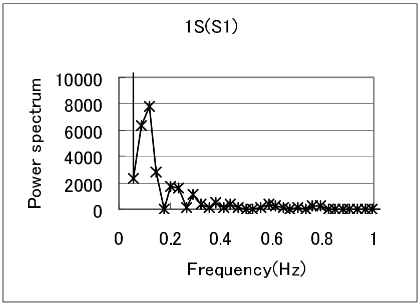

Fig. 1. Power spectrum of LF/HF (PD) at 1 s for S1 (Experiment 1)

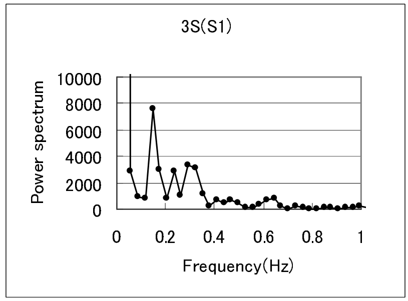

Fig. 2. Power spectrum of LF/HF at 3 s for S1 (Experiment 1)

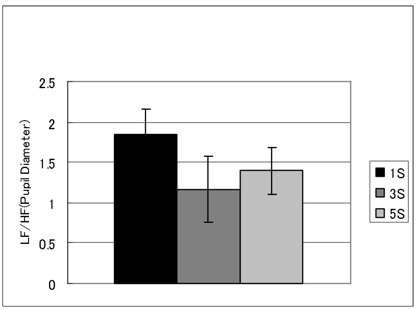

Fig. 3. Power spectrum of LF/HF (PD) at 5 s, for S1 (Experiment 1)

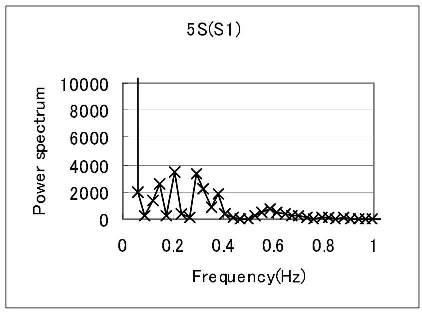

Fig. 4. Average of LF/HF (PD) at 1 s, 3 s and 5 s (Experiment 1)

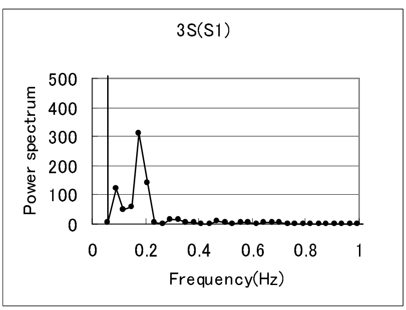

Fig. 5. Power spectrum of LF/HF (HR) at 1 s, for S1 (Experiment 1)

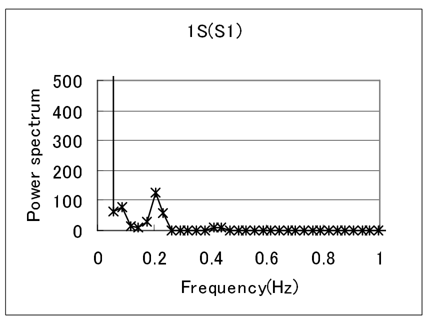

Fig. 6. Power spectrum of LF/HF (HR) at 3 s, for S1 (Experiment 1)

Procedure: The subjects performed the categorizing tasks in response to audio stimuli presented at different time intervals (1, 3 and 5 seconds). Pupil diameter (PD) and heart rate (HR) were monitored throughout the trial. These stimuli induced psychological stress in the subjects. Their task was to answer whether the word presented via the headphones belonged to the specified single category or not. There were 6 categories: Vegetables, Fruit, Fish, Insects, Birds, and Mammals. Each trial lasted about 60

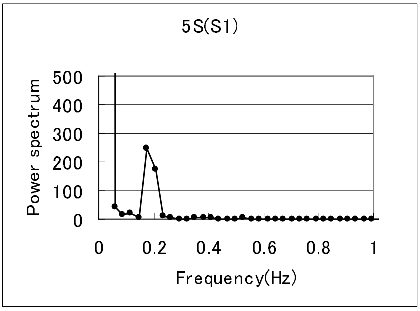

Fig. 7. Power spectrum of LF/HF (HR) on 5 s, for S1 (Experiment 1)

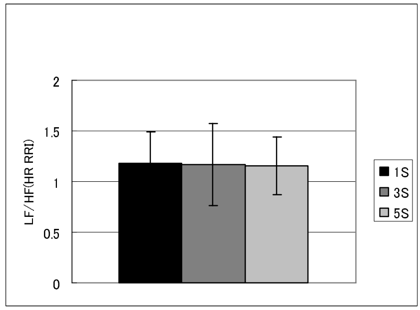

Fig. 8. Average of LF/HF (HR) on 1 s, 3 s and 5 s (Experiment 1)

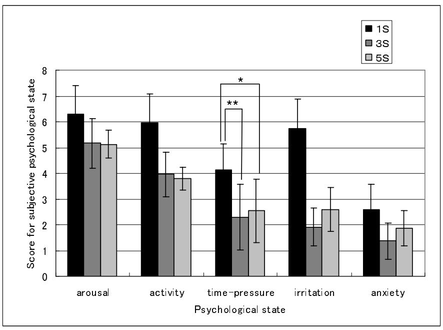

Fig. 9. Score for subjective assessment of psychological state (Experiment 1)

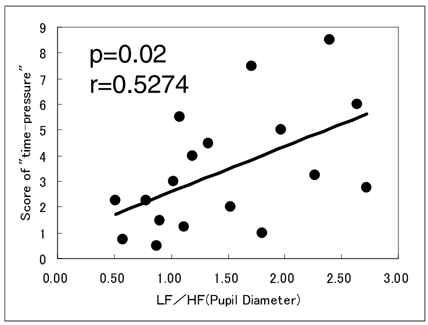

Fig. 10. Correlation between LF/HF (PD) and 'time-pressure' (Experiment 1)

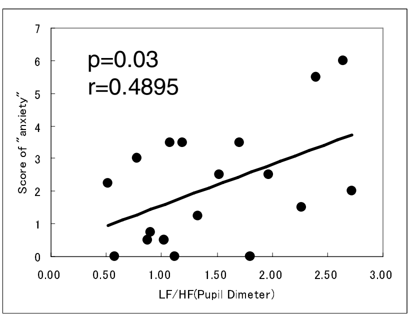

Fig. 11. Correlation between LF/HF (PD) and 'anxiety' (Experiment 1)

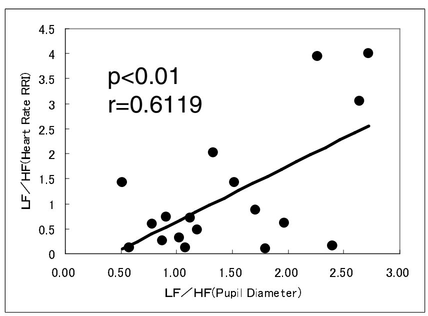

Fig. 12. Correlation between LF/HF (PD) and LF/HF (HR) (Experiment 1)

seconds. During each trial, the time interval between each test word was set at a constant value of 1, 3, or 5 seconds. After each trial, the subject gave a subjective evaluation of their psychological state ('arousal,' 'activity,' 'time-pressure,' 'irritation,' and 'anxiety'), on a score of 0 to 10. The order of the time interval tested was changed for each subject.

2.2 Results

PD variability: Figures 1, 2 and 3 show the power spectrum of PD variability for the conditions of 1 s, 3 s and 5 s for subject S1, respectively. In the case of workload stress for 1 s, the power spectrum of PD variability peaked at around 0.1 Hz (Fig. 1). That for the 3-s condition peaked at around 0.15 Hz (Fig. 2), and that for the 5-s condition peaked at around 0.2 Hz and 0.32 Hz (Fig. 3). The maximum of peak frequency at 5 s shifted to higher frequency than that for 1 s and 3-s conditions. Figure 4 shows the average LF/HF of PD variability across six subjects for each time interval. There was no significant difference in the LF/HFs.

HR variability: Figures 5, 6 and 7 show the power spectrum of HR variability for the conditions of 1 s, 3 s and 5 s respectively for subject S1. In the case of workload stress at 1 s, power spectrum of heart rate variability peaked at around 0.08 and 0.2 Hz (Fig. 5). That for the 3-s and 5-s conditions peaked at around 0.2 Hz (Fig. 6) and around 0.20 Hz (Fig. 7), respectively. Figure 8 shows the average LF/HF of HR variability across six subjects for the 1-s, 3-s and 5-s time intervals. There was no significant difference in the LF/HFs. This is probably due to the large individual differences.

Subjective evaluation of psychological state: Figure 9 shows the average scores of subjective evaluation of psychological state across eight subjects. The horizontal axis indicates the psychological state items, and the vertical axis indicates the score. For all the items, the scores tended to be higher for the 1-s condition. The score for 'time-pressure' for the 1-s condition was significantly higher than that for 3 s ($p < 0.01$) and also higher than that for 5 s ($p < 0.05$).

Correlation among LF/HF of PD variability, LF/HF of HR variability and Subjective evaluation of psychological state: A significant correlation was observed between the LF/HF of PD variability and the score for 'time-pressure' ($p = 0.02$, $r = 0.5273$) (Fig. 10) and between the LF/HF of PD variability and the score for 'anxiety' ($p = 0.03$, $r = 0.4895$) (Fig. 11). Moreover, a significant correlation was observed between the LF/HF of PD variability and that of HR variability ($p < 0.01$, $r = 0.6119$) (Fig. 12).

3 Experiment 2: Task with Cognitive Load

In Experiment 2, pupil diameter (PD) and heart rate (HR) were monitored while the subjects performed categorizing tasks in response to audio stimuli with varying specified numbers of categories. These stimuli induced different levels of cognitive stress in the subject.

3.1 Methods

Subjects: Six adults aged from their 20s to their 50s participated in this experiment. All the subjects had taken part in Experiment 1.

Measurements: Subjective evaluation of psychological state through interviews, pupil diameter (PD) monitored by infrared video camera and heart rate (HR) monitored by electrocardiogram (ECG), as in Experiment 1. All the apparatus used in this experiment was the same as in Experiment 1. The LF/HF of PD variability and that of HR variability were also calculated in the same way as in Experiment 1.

Procedure: The subjects performed the categorizing task in response to audio stimuli. The time interval was set at a constant 2 seconds in all trials. Each trial lasted about 70 seconds. The number of categories to which the word might belong was set at 1 (level 1: 1L), 2 (level 2: 2L), 3 (level 3: 3L) or 4 (level 4: 4L). Increasing the number of categories raised the level of cognitive-task difficulty. We used the same categories for the task as in Experiment 1: Vegetables, Fruit, Fish, Insects, Birds, and Mammals. After each trial, the subjects made a subjective evaluation of their psychological states ('arousal,' 'activity,' 'time-pressure,' 'irritation,' 'anxiety'), on a score of 0 to 10. The order of cognitive load levels was changed for each subject.

3.2 Results

PD variability: Figure 13, 14, 15 and 16 show power spectra of PD variability for the conditions of 1L, 2L, 3L and 4L for subject S1. In the case of a workload level of 1L, the power spectrum of PD variability showed a peak value around 0.18 Hz (Fig. 13). In the case of a workload level of 2L or 3L, the peak frequency was around 0.15 Hz (Fig. 14, Fig. 15). For a workload level of 4L, the peak frequency was around 0.08 Hz (Fig. 16). The peak frequency of power spectrum of PD variability tended to shift to a lower frequency on increasing the level of cognitive load. There was no significant difference in the average LF/HF of PD variability across the six subjects during the present task with different levels of cognitive load. (Fig. 17).

HR variability: There was no significant difference in the average LF/HF of HR variability across the six subjects for different conditions of cognitive load (1L, 2L 3L and 4L) (Fig. 18). However, the LF/HF of HR variability showed wide variation among subjects.

Subjective evaluation of psychological state: Figure 19 shows the average scores of subjective evaluations of psychological state across eight subjects. The horizontal axis indicates the items of psychological state, and the vertical axis indicates the score. For all items except 'time pressure,' the scores increased as the level of cognitive work-load increased.

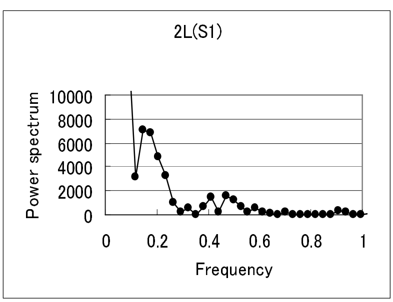

Fig. 13. Power spectrum of LF/HF (PD) on 1L for S1 (Experiment 2)

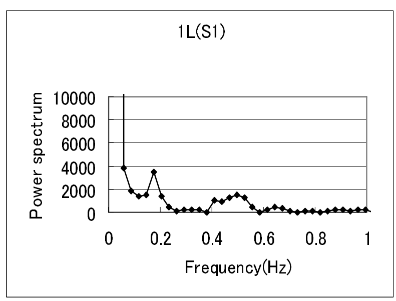

Fig. 14. Power spectrum of LF/HF (PD) on 2L for S1 (Experiment 2)

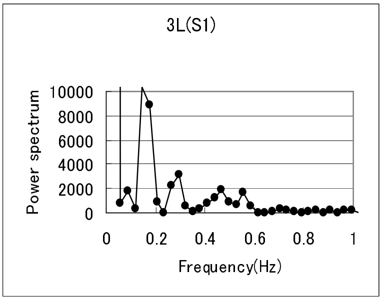

Fig. 15. Power spectrum of LF/HF (PD) on 3L for S1 (Experiment 2)

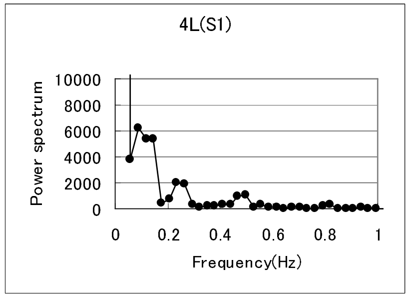

Fig. 16. Power spectrum of LF/HF (PD) on 4L for S1 (Experiment 2)

Correlation among LF/HF of PD variability, LF/HF of HR variability and Subjective evaluation of psychological state: There were no significant correlations observed between the LF/HF of PD variability and each of the other two measured indices (the subjective score of psychological states and the LF/HF of HR variability). According to our previous study [4], it is possible that the optimum frequency bands for defining LF/HF of PD and HR variability depend on the kind of task. For calculating the LF/HF shown in Fig. 17, we used 0.04–0.15 Hz for the low frequency band (LF) and 0.15–0.5 Hz for the high frequency band (HF) as in Experiment 1. Here, we recalculated the LF/HF of PD and HR variability using adjusted bands as follows:

Definition A: (LF: 0.08–0.18 Hz, HF: 0.18–0.5 Hz)
Definition B: (LF: 0.08-0.20 Hz, HF: 0.20-0.5 Hz)
Definition C: (LF: 0.10-0.20 Hz, HF: 0.20-0.5 Hz)

As a result of adjusting the bands for defining LF/HF, a significant correlation was observed between the LF/HF of PD variability using Definition A and the subjective score of 'arousal' ($p = 0.02$, $r = 0.4857$) (Fig. 20). A significant correlation was also observed between the LF/HF of PD variability using Definition A and the LF/HF of HR variability using Definition C ($p = 0.04$, $r = 0.4166$). Similarly, a pattern of correlation was observed between the LF/HF of PD variability using Definition A and the LF/HF of HR variability using Definition A ($p < 0.1$, $r = 0.3642$).

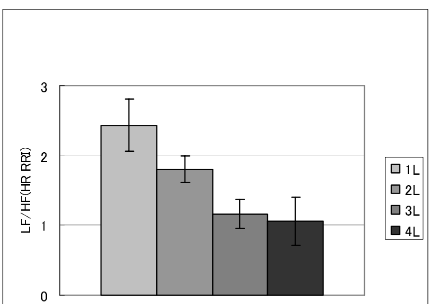

Fig. 17. Average of LF/HF (PD) on 1L, 2L, 3L and 4L (Experiment 2)

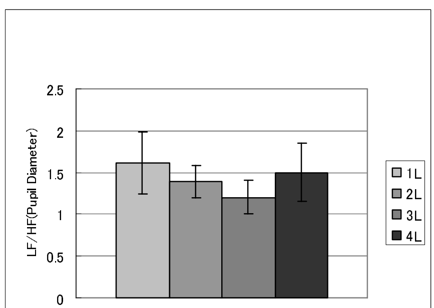

Fig. 18. Average of LF/HF (HR) on 1L, 2L, 3L and 4L (Experiment 2)

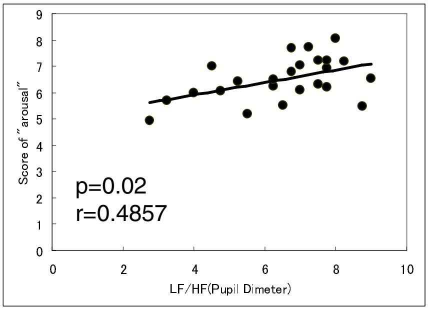

Fig. 19. Score for subjective evaluation of psychological state (Experiment 2)

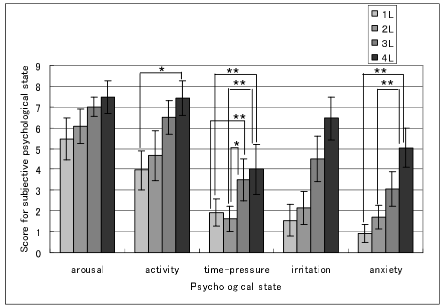

Fig. 20. Correlation between LF/HF (PD) and 'arousal' (Experiment 2)

4 Discussion

The results of Experiment 1 show that subjective responses of 'arousal,' 'activity' and 'time-pressure' increased on increasing the level of the task workload. The shape of the curve for LF/HF of PD variability was U-shaped, bottoming at the workload with the 3-s interval, and significant correlation was observed between LF/HF of PD variability and the score for 'time-pressure' and 'anxiety,' indicating the possibility that high LF/HF value of PD variability at 1 s might reflect the mental stress caused by too high a workload, and high LF/HF value of PD variability at 5 s might reflect the mental stress caused by too little a workload.

Moreover, the maximum peak frequency of power spectrum of PD variability of the 5 s interval condition shifted to a higher frequency than those for 1-s and 3-s intervals. This indicates that the peak frequency of the power spectrum of PD variability value might reflect workload level. In Experiment 1, a significant correlation was also observed between the LF/HF of PD variability and that of HR variability. These results therefore indicate that LF/HF of PD variability is an evaluation index of mental stress, and could be used as a substitute for LF/HF of HR variability when measuring mental stress.

The results of Experiment 2 show that subjective responses of 'arousal', 'activity,' 'irritation' and 'anxiety' increased with increasing the level of cognitive load. These results indicate that the settings of each level of difficulty were appropriate for inducing different degrees of mental stress. However, the curve for LF/HF of PD variability was U-shaped curve and bottomed at 3L, and LF/HF at 1L and 4L (the lowest and highest cognitive task level, respectively) were higher than those for 2L and 3L. These results indicate that higher LF/HF of PD variability at 4L and 1L might be due to the mental stress caused by too high a workload and too low a workload, respectively. It is possible that the optimum task level might be at the lowest point of LF/HF of PD variability.

Moreover, the peak frequency of the power spectrum of PD variability that took maximum value shifted to a lower frequency on increasing the cognitive level. This indicates that the peak frequency of the power spectrum of PD variability that takes a maximum value might reflect workload stress.

The optimum frequency bands for LF/HF of PD variability in which significant correlations with mental stress were observed in Experiment 1 were different from those in

Experiment 2. The optimum bands used in the analysis to indicate stress from the cognitive load as presented in Experiment 2 shifted to a higher frequency than that from the time pressure as presented in Experiment 1. These facts indicate the possibility that the optimum bands for LF/HF of PD and Heart Rate variability may change according to type of task.

5 Conclusions

The results in Experiment 1 and 2 show that subjective responses to psychological states ('arousal', 'activity,' 'time pressure', 'irritation' and 'anxiety') increased on increasing the task workload. Moreover, using the same frequency band as that of heart rate variability (LF/HF), during the task with time pressure in Experiment 1 revealed a significant correlation between the ratio of lower-to higher-frequency components (LF/HF) of PD variability and subjective psychological state. A significant correlation was also observed between LF/HF of PD variability and LF/HF of HR variability in Experiment 1. During the cognitive load task in Experiment 2, a significant correlation was observed between subjective psychological state and LF/HF of PD variability, as calculated from the different frequency band, as that of HR variability.

These results indicate that LF/HF of PD variability is an effective index of mental stress, and could be used as a substitute for LF/HF of HR variability when measuring mental stress.

Acknowledgements

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