A New Scatter Plot Stress Evaluation Method Using Photo-Plethysmography

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Abstract

A new stress evaluation method is proposed to visualize the balance of the autonomic nervous system and to distinguish between eustress and distress in this paper. Against the conventional method, a new stress-evaluation scatter plot is suggested with new axis parameters on the vertical and horizontal axes corresponding to the sympathetic and parasympathetic nervous systems, respectively. 4 zones are presented on the proposed scatter plot. The first quadrant enables to show the well-balanced autonomic nervous system. The verification experimental results have shown that the proposed stress evaluation method is worth further investigation. Questionnaires obtained after experiments also show the validity of proposed method.

1 Introduction

Stress is currently recognized as an effect which has a major impact on people's wellbeing. Stress is caused by many environmental factors, hence stress is major social problem. There are many ways to evaluate stress such as exploring the response of autonomic nervous system, blood chemistry changes, and the use of questionnaires. For evaluating the autonomic nervous system, the balance of the functions of its sympathetic and parasympathetic nervous systems needs to be evaluated because this balance has a major effect on the human mind and body. The autonomic nervous system is influenced by stress, and this can cause blood circulation fluctuations. The sympathetic and parasympathetic nervous systems operate on blood vessels antagonistically. With an increase in the activity of the sympathetic nervous system, blood vessels contract, restricting blood flow. This leads to high blood pressure. On the other hand, when the parasympathetic nervous system is excessively active, blood vessels relax too much. Then blood flow stagnates. Thus when the activity of either the sympathetic or parasympathetic nervous system increases too much, blood doesn't flow well. Nevertheless it has also been reported that when both the sympathetic and parasympathetic nervous system are operating at a high level, they work together well [1]. Accordingly “well-balanced” is defined in this study as the state where both are at a high level.

To quantify the effects of stress on the working public, a mandated workplace stress check has been introduced by the Ministry of Health, Labor and Welfare of Japan from December 2015. The stress check questionnaire puts strong emphasis on identifying stress which has a negative influence on both the body and mental state, i.e. distress. However, it is known that the stress which has a positive influence, eustress, also exists. Figure 1 shows some examples of eustress and distress. Eustress and distress need to be distinguished not only for ordinary health control of employees but also for the improvement of the working environment. The purpose of our study is to evaluate the balance of the autonomic nervous system and to distinguish between eustress and distress. In this paper, stress evaluation parameters obtained from photo-plethysmography are investigated and a new stress evaluation method is proposed and experimentally evaluated.

Figure 1: Some examples of eustress and distress [2]

2 Parameters for Stress Evaluation

2.1 Conventional Parameters and Method

2.1.1 The Autonomic Nervous Systems
Figure 2 shows part of the structure of the human nervous system and effector organs for the sympathetic and parasympathetic nervous system. The human nervous system is divided into the central and peripheral nervous system. The peripheral nervous system is also divided into the somatic and autonomic nervous system. The autonomic nervous system controls body functions automatically. The autonomic nervous system consists of the sympathetic and the parasympathetic systems. As an example of their operation, the sympathetic nervous system operates on blood pressure fluctuation and the parasympathetic nervous system operates on both blood pressure and breath fluctuation. The sympathetic and parasympathetic nervous systems operate mostly antagonistically. For instance the parasympathetic nervous system dampens the function of the sympathetic nervous system to stop it overworking. For that reason, the sympathetic and parasympathetic nervous systems are often compared to the gas pedal and brake in an automobile. However both “gas pedal” and “brake” are ready to be active at the same time in the autonomic nervous system [3]. It is considered that the sympathetic and parasympathetic nervous system should be well-balanced to maintain good health. Thus the balance of the autonomic nervous systems is evaluated in our study.

2.1.2 Conventional Stress Evaluation Method

HF (High Frequency) and LF (Low Frequency) components from vital sign measurements such as Electrocardiogram (EKG) or Photo-Plethysmography (PPG) are often used as stress evaluation parameters for the autonomic nervous system. HF and LF can be calculated as follows. Frequency analysis is performed on a spline interpolation graph of the R to R Interval (RRI) or the Peak to Peak Interval (PPI) for EKG or PPG respectively. Then the PSD integrated value is obtained in either an HF or LF range. HF has a range of 0.15-0.4 Hz, which corresponds to the breath fluctuation rate. Breath fluctuation is affected by the parasympathetic nervous system. For example, the HF PSD increases when the parasympathetic nervous system is active. Thus HF is used as a parasympathetic nervous system evaluation parameter. On the other hand LF has a range of 0.04-0.15 Hz which corresponds to Mayer waves: blood pressure fluctuations. Mayer waves are influenced by both the sympathetic and the parasympathetic nervous system. Like HF, the LF PSD increases when both the sympathetic nervous system and the parasympathetic nervous system are active. Therefore LF/HF is used as a sympathetic nervous system evaluation parameter. Figure 3 shows the method of calculating LF and HF, frequency range and the relationship with the autonomic nervous system.

These parameters are used in the HF-LF/HF scatter plot model, a common stress evaluation method, as shown in Figure 4 [4]. Stress is evaluated by the activity level of the autonomic nervous system. LF/HF and HF, which represent the sympathetic and parasympathetic nervous system, are used for the vertical and horizontal axes respectively. Zone 3 shows the neutral state where level of both sympathetic and parasympathetic nervous systems are low. Zone 2 shows the distress state because the activity level of the sympathetic nervous system is high and it unbalances the autonomic nervous system. Zone ☆ shows
the relaxation state because the activity of the parasympathetic nervous system is high. However, this scatter plot can’t describe the area where the sympathetic and parasympathetic nervous system are well-balanced i.e. eustress (Zone 1 in Fig. 4) because HF is a parameter in both vertical and horizontal axes. Consequently different parameters are needed for the vertical and horizontal axes to describe Zone 1.

2.2 Parameters and Method

2.2.1 Photo-Plethysmography (PPG)

As mentioned in 2.1.2, candidate parameters for autonomic nervous system evaluation are considered here. Direct frequency analysis of raw signals are used instead of frequency analysis after spline interpolation. EKG is not appropriate for direct frequency analysis because of the sharpness of its waveform, whereas a pulse wave is more appropriate for direct frequency analysis because of its smoothness. Therefore we use a photo-plethysmography (PPG) pulse signal which optically detects changes caused to the pulse wave under the influence of the autonomic nervous system in this study.

2.2.2 Parameter for the Sympathetic Nervous System Evaluation

A candidate parameter for evaluating the sympathetic nervous system is considered here. The first harmonic wave (H1), which appears around the pulse rate frequency, has been linked to the sympathetic nervous system and is obtained from PPG. Direct frequency analysis is used without spline interpolation. It has been reported that liver function is affected by a highly active sympathetic nervous system [5] and this affects H1 [6]. This is a reason why H1 is adopted as a parameter for the sympathetic nervous system.

Figure 4: The HF-LF/HF scatter plot model after [4]

H1 is calculated as follows. Short-time Fourier transformation (STFT) is performed on the PPG signal with hamming windows. H1 is the PSD integrated value of the first harmonic wave which comes from pulse rate, and appears around 1Hz [6]. The above H1 value is then normalized by averaging with the H1 of the rest state. This value is defined H1n. There are two reasons for normalization: to set zone boundaries for our new stress evaluation method, and to make a parameter which can be universally applied to any test subject by removing individual differences. Figure 5 shows the method used to calculate H1n in this study and the difference from the method used to obtain LF and HF. There are a few reports on the close correspondence of H1n to the activity of the sympathetic nervous system as shown in Figure 6 [7]. H1n is obtained through a stress load experiment which consists of 3 states: rest, stress and recovery. H1n decreases when the sympathetic nervous system is active during the stress state and increases during the recovery state when compared to the rest state. Since the reciprocal 1/H1n increases under the same circumstances, 1/H1n is used for the vertical axis in the scatter plot in place of LF/HF.

Figure 5: Method used to calculate H1n and differences from the method to obtain LF and HF
2.2.3 Parameter for Parasympathetic Nervous System Evaluation

A candidate parameter for evaluating the parasympathetic nervous system is considered here. The Lorenz plot (LP) is a method for evaluating the function of the autonomic nervous system. It visualizes the fluctuation of the PPI value. The n-th and n+1-th data are plotted on the horizontal and vertical axes, respectively. For describing the spread of the PPI values in the LP graph, S is introduced as a numerical parameter. \( \sigma_x \) and \( \sigma_{-x} \) are the standard deviation from (0,0) on the y=x and y=-x axes after projection, respectively. S is equal to \( \pi \times \delta_x \times \delta_{-x} \) [8]. Figure 7 shows the relationship between the LP and S graphically. There is close correlation between S and HF [8]. As mentioned before, HF is used as a parameter for evaluating the parasympathetic nervous system. Thus S also can be used as a parameter for evaluating the parasympathetic nervous system. The S value is normalized by averaging with the rest state value of S, for the same reasons as H1 was normalized in 2.2.2. This value is defined as Sn. When the parasympathetic nervous system is active, Sn increases. Hence Sn is used for the horizontal axis in the scatter plot in place of HF.

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S = \pi \times \sigma_x \times \sigma_{-x}
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Figure 7: Relationship between LP and S after [8]

3 New Stress Evaluation Method

3.1 Zone Classification

Using these two new parameters, a new scatter plot which uses 1/H1n for the vertical axis and Sn for the horizontal axis is investigated. The balance of the autonomic nervous system and the distinction between eustress and distress are investigated with the new scatter plot. This is illustrated in Figure 8. The N area (1,1) in the proposed scatter plot corresponds to the conventional neutral area seen in Figure 4. Thus newer axes and boundary have been introduced. We use x=1 and y=1 as the boundary between zones because we would like to have the individual rest state readings as the origin during experiments. This will allow us to evaluate stress response relatively between subjects. As can be seen, there are four zones covering the four basic balance conditions of the nervous system: high parasympathetic and high sympathetic, low parasympathetic and high sympathetic, low parasympathetic and low sympathetic, and high parasympathetic and low sympathetic. These are zones (1) to (4), respectively. By investigating Zone (1) and (2), it will become possible to observe a well-balanced, highly active autonomic nervous system and to distinguish eustress from distress. When data points are located in the vicinity of the straight line y=x, the state of the autonomic nervous system of subject is regarded as balanced, as it means that the sympathetic and parasympathetic nervous system correspond one to one.

Figure 8: Coordinate system for the new stress evaluation method
3.2 New Stress Balance Evaluation and Stress Distinction

N is the balance point of the autonomic nervous system as measured during the experimental rest time. Data points obtained from PPG from subjects lie in certain zones. Explanation of each zone follows.

Zone (1): When data points are contained in this area, the state of the autonomic nervous system of the subject is regarded as the best balanced among the 4 zones because levels of both sympathetic and parasympathetic nervous system are high. Furthermore when plot points are close to the line y=x, it shows a well-balanced state as mentioned in 3.1. Thus body and mind condition is considered to be the best.

Zone (2): When data points are contained in this area, the state of the autonomic nervous system of the subject is regarded as unbalanced because the activity level of the sympathetic and parasympathetic nervous systems is high and low respectively. Thus the body and mind condition is considered to be poor.

Zone (3): When data points are contained in this area, the state of the autonomic nervous system of the subject is regarded as balanced. Although the sympathetic and the parasympathetic nervous system are balanced, the activity of both are low. Thus the subject is considered to have a tendency to get tired easily.

Zone (4): When data points are contained in this area, the state of the autonomic nervous system of subject is regarded as unbalanced because the level of the sympathetic and parasympathetic nervous system is low and high respectively. Thus the subject is considered to be depressed.

Zones (1) and (2): Both zones, where y>1, are regarded as stress loaded states. When data points are contained in these areas, it shows a stress loaded state because the activity of the sympathetic nervous system is high. This means that the subject experiences stress.

Stress distinction: The area, where y>>1 and data points are inside zone (1), is regarded as the state where the subject experience eustress because the autonomic nervous system is in the best balance although stress is induced. On the other hand, the area, where y>1 and plot points are inside zone (2), is regarded as the state where the subject experiences distress because the autonomic nervous system is unbalanced and stress is induced.

4 Verification Experiments

4.1 Experimental Procedures

There were two kinds of experiments. The first was a movie-watching experiment aiming to induce a distress condition. The second was a classical music listening experiment aiming to induce a well-balanced condition. PPG measurement was performed using a PowerLab4/26 data acquisition unit (ADinstruments Pty Ltd) throughout the experiments. The PPG measurement area was the right index finger of the subject.

Movie-Watching Experiment

The subject watched a movie, “Cloverfield”, which was taken with a hand-held camera, using a Head-Mounted Display (HMD). They were allowed to stop watching the movie if they felt ill or distressed. They also filled in a questionnaire on their experience after the experiment. Figure 9 (a) shows the procedure of this experiment. The experiment consists of 3 states: rest, movie watching and recovery. They rested for 30 minutes. Then they watched the movie with the HMD for 90 minutes. Finally they recovered for 36 minutes. They were seated throughout. There were 4 subjects in this experiment.

Classical Music Listening Experiment

The subject listened to classical music (Mozart’s K 218 and other pieces [9]) using noise-canceling headphones throughout this experiment. They answered the experience questionnaire 4 times during the experiment. Figure 9 (b) shows the procedure of this experiment. The experiment also consisted of 3 states: rest, listening to classical music and recovery. They rested for 15 minutes. Then they listened to Mozart using the noise-canceling headphones for 30 minutes. Finally they recovered for 15 minutes. They were seated throughout. There were 3 subjects in this experiment.
Figure 9: Procedures for the two experiments:
   a) movie-watching experiment
   b) classical music listening experiment

4.2 Analysis Procedure

Experimental data were analyzed by frequency domain. Analysis details are as follows: STFT of PPG signal data were performed with Matlab R2014b. Sampling frequency was 1 kHz, window function was Hamming window, window interval was 10 sec. and overwrap was 0%. Sn was calculated per 100 pulse beats and H1n was calculated per 10 sec. Therefore 1/H1n data points were averaged to agree with those of Sn.

5 Results and Discussion

5.1 Movie-Watching Experiment

Figure 10 shows the result of movie-watching experiment for one subject using our stress evaluation method. Blue plot (○), red plot (*) and green plot (□) show rest, watching movie, and recovery respectively.

First, the balance of the autonomic nervous system is evaluated using Figure 10. The plot is close to N during rest. On the other hand, the plot is in zone (2) while watching the movie, i.e. the autonomic nervous system is unbalanced. Then plot comes back close to N again during recovery. This shows balance of the autonomic nervous system eventually reaches the same area as during rest. Distinguishing the stress type, we see that when the subject was watching the movie, they were considered to be distressed because there are a lot of data points in zone (2).

According to the post-experimental questionnaire, the subject answered that they felt stress building up gradually with time while watching the movie. For other 3 subjects, it has been found that the results from proposed method mostly match the answers of post-experimetal questionnaire. This suggests our proposed stress evaluation method is effective.

5.2 Classical Music Listening Experiment

Figure 11 shows the results of the classical music listening experiment for one subject using our proposed stress evaluation method. Blue plot (○), light blue plot (*) and green plot (□) show rest, listening to classical music, and recovery respectively.

First we evaluated the balance of the autonomic nervous system. The plot is close to zone N during rest. On the other hand, the plot is in zone (1) when the subject is listening to Mozart or recovering. It shows the autonomic nervous system is well-balanced. Distinguishing the stress type, we can see that there are more data points over the line y=x and at y>>1 compared to Figure 10. When the subject was listening to classical music, they are thought to be experiencing eustress because there are a lot of data points in the y>>1 area inside of (1).

According to the post-experimental questionnaire, the subject said that they felt vigorous. For other 2 subjects, it has been also found that the results from proposed method mostly match the answers of post-experimental questionnaire. This implies our proposed stress evaluation system has the potential to visualize the feelings of test subjects.

Furthermore, when data plots are under the line y=x inside zone (1), it means that the parasympathetic nervous system is relatively active. Considering that the parasympathetic nervous system works to relax the body, it also implies that proposed stress evaluation system has potential to visualize relaxation, too. It is shown that more data points lie under the line y=x in Figure 11 compared to Figure 10. Thus beyond the achieved goal to induce a
well-balanced condition in this classical music listening experiment, it is found that the proposed stress evaluation method has the potential to visualize not only eustress but also relaxation.

Through these two experiments it has been possible to evaluate the balance of the autonomic nervous system and to distinguish eustress from distress. It is under investigation to compare experimental results from the proposed method with those of conventional method. Future work will include: increasing the number of subjects for statistical hypothesis testing, more experimental contents (movies, music), the effects of experimental repetition, improvement of normalization, checking the stress effect of HMD-wearing.

6 Conclusion

A new stress evaluation method has been demonstrated to show the balance of the autonomic nervous system and to distinguish eustress from distress by using new parameters obtained by PPG. The experiments showed the validity of the proposed stress evaluation method.

References