Assessment of Effects of Visually-Induced Motion Sickness Using Physiological Index Obtained from Photoplethysmography

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Abstract. A human watching a swaying image displayed on a wide-field display or screen sometimes suffers from visually-induced motion sickness (VIMS) that causes symptoms related to the autonomic nervous system such as nausea, vomiting, and dizziness. The previous study indicated that the maximum cross-correlation coefficient ($\rho_{\max}$) between blood pressure and heart rate whose frequency components are limited to the neighborhood of 0.1Hz is a useful index to evaluate the effects of VIMS on humans. The present study has proposed a new method for obtaining $\rho_{\max}$ with measurement of neither continuous blood pressure nor ECG but using only finger photoplethysmography (PPG). In this study, heart rate was obtained from the foot-to-foot-interval of the PPG signal, and blood pressure-related information was obtained from the parameter extracted from using the independent component analysis. The adequacy of the proposed method was evaluated by two experiments with the Valsalva maneuver and a swaying video image. The experimental results have shown that the proposed method could extract the independent component related to blood pressure. In addition, the effects of visually-induced motion sickness could be estimated with the independent component.

Introduction

A human watching a moving image displayed on a wide field display or screen often suffers from visually-induced motion sickness (VIMS) that induces symptoms related to the autonomic nervous activity such as nausea, vomiting, and dizziness. The previous study (Sugita *et al.*, 2005) reported that the maximum cross-correlation coefficient ($\rho_{\max}$) between blood pressure variability (BP) and heart rate variability (HR) whose frequency components were limited in the neighborhood of 0.1Hz was a useful index to evaluate the effects of VIMS on humans. The present study has proposed a new method for obtaining $\rho_{\max}$ with measurement of neither continuous blood pressure nor ECG but using finger photoplethysmography (PPG) only. In this study, *HR* was obtained from the foot-to-foot-interval (*FFI*) of the PPG signal, and *BP*-related information was extracted from feature vectors of the PPG signal by using the independent component analysis (ICA).

Experiments with the Valsalva maneuver and with the presentation of a swaying video image which may induce VIMS were carried out to verify the validity of the proposed method.

Methods

Independent Components Analysis. The ICA used in our method is as follows:

1) Let $x_1(k)$, $x_2(k)$, ... , $x_m(k)$ be m variables extracted from the PPG signal at the k-th beat. Define a feature vector $\boldsymbol{x}(k)$ as $\boldsymbol{x}(k) = [x_1(k), x_2(k), \ldots, x_m(k)]^T$.
2) Let $s_1(k)$, $s_2(k)$, ... , $s_n(k)$ be n unknown physiological parameters which are independent of one another at the k-th beat. Define a parameter vector $\boldsymbol{s}(k)$ as $\boldsymbol{s}(k) = [s_1(k), s_2(k), \ldots, s_n(k)]^T$.
3) Assume that the feature vector $\boldsymbol{x}(k)$ is given by a linear combination of $s_1(k)$, $s_2(k)$, ... , $s_n(k)$ as follows:

$$\boldsymbol{x}(k) = \boldsymbol{A}\boldsymbol{s}(k) \quad (1)$$

where, an $m \times n$ matrix $\boldsymbol{A}$ represents an unknown constant mixing matrix consisting of coefficients of the liner combination. Let K be the number of beats observed in an experiment. Define an $m \times K$ matrix $\boldsymbol{X}$ and an $n \times K$ matrix $\boldsymbol{S}$ as $\boldsymbol{X} = [\boldsymbol{x}(1), \boldsymbol{x}(2), \ldots, \boldsymbol{x}(K)]$ and $\boldsymbol{S} = [\boldsymbol{s}(1), \boldsymbol{s}(2), \ldots, \boldsymbol{s}(K)]$, respectively. Thus, the matrix $\boldsymbol{X}$ is assumed to be given by $\boldsymbol{S}$ as follows:

$$\boldsymbol{X} = \boldsymbol{A}\boldsymbol{S} \quad (2)$$

4) The ICA is applied to estimate the mixing matrix $\boldsymbol{A}$ from the matrix $\boldsymbol{X}$. The independent component $\boldsymbol{S}$ can be obtained by

$$\boldsymbol{S} = \boldsymbol{A}^{+}\boldsymbol{X} \quad (3)$$

where $\boldsymbol{A}^{+}$ is the pseudoinverse matrix of $\boldsymbol{A}$.

In this study, we used the first fixed point algorithm (Fast-ICA) presented by Hyvärinen and Oja to linearly separate $\boldsymbol{S}$ from $\boldsymbol{X}$ (Hyvärinen, 1999; Hyvärinen and Oja, 1997). In addition, the numbers of the feature variables m and the independent variables n were set to 7 and 4, respectively.

Figure 1 shows an example of the PPG signal. In this figure, 7 feature variables used in the present study are illustrated. These are defined every beat as follows:

1) *FFI*: the foot-to-foot interval of the PPG
2) t_d: the interval from the time maximizing the PPG to the time minimizing the PPG
3) $t_{maxslope}$: the time maximizing the slope of the PPG
4) PW_{bias}: the minimum value of the PPG
5) PW_{max}: the maximum value of the PPG
6) DPW_{max}: the value of the PPG at $t_{maxslope}$
7) *NPWA*: the area of the PPG normalized by *FFI*

These parameters include information on hemodynamic state such as blood pressure and vascular compliance. For example, the parameter *NPWA* shows the mean value of the pulsatile component of arterial blood volume and is a candidate of substitution of *BP*.

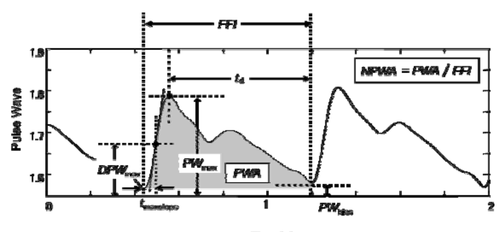

Figure 1. Definition of feature variables $x_1(k)$, $x_2(k)$, ... , $x_m(k)$; m = 7 and the normalized pulse wave area (*NPWA*)

Experiments. In this study, healthy 15 subjects (12 males and 3 females, 23.6 ± 2.6 yrs) participated in two consecutive experiments. The first experiment was the Valsalva maneuver to obtain the mixing matrix $\boldsymbol{A}$ for each subject. The second one was the experiment in which the subject watched a swaying video image.

1) Experiment I (Valsalva maneuver):

The Valsalva maneuver was performed by having the subject conduct a maximal, forced expiration against a closed glottis and keeping this condition for 1 minute. In general, baroreflex sensitivity of the subject on the Valsalva maneuver decreases and thus $\rho_{\max}$ may decrease. ECG, continuous blood pressure and finger PPG of the subject were measured during the experiment. Figure 2 represents the protocol of the experiment.

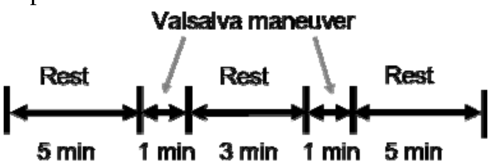

Figure 2. Protocol of Experiment I.

2) Experiment II (presentation of a swaying video image):

After Experiment I, the subject watched a swaying video image projected by a LCD projector as shown in Fig. 3. The video was taken by a handheld camera swayed intermittently and thus the subject was at an increased risk for VIMS. Physiological parameters measured in this experiment were the same as in the Valsalva maneuver. The protocol of the experiment is shown in Fig. 4. After the second rest, the simulator sickness questionnaire (SSQ) (Kennedy *et al.*, 1993) was charged on the subject. The total score (*TS*) of the SSQ is calculated to obtain a subjectively evaluated intensity of VIMS.

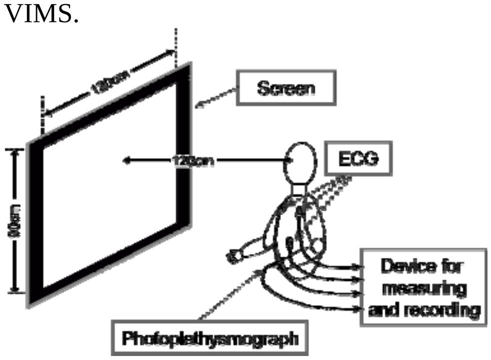

Figure 3. Experimental setup of Experiment II.

Figure 4. Protocol of Experiment II.

Analyses. Experiment I (Valsalva maneuver), the mixing matrix $\boldsymbol{A}$, its pseudoinverse $\boldsymbol{A}^+$ and the independent component matrix $\boldsymbol{S}$ were calculated with the ICA for each subject. Define n independent component time series IC_l; l = 1, 2, ... , n as $IC_l = \{s_l(1), s_l(2), \ldots, s_l(K)\}$ with the data size of K corresponding to the length of the experiment.

Let time series $\rho_{\max}(BP)$ and $\rho_{\max}(IC_l)$ denote $\rho_{\max}$ between HR and BP, and $\rho_{\max}$ between HR and an independent component IC_l, respectively.

Let l^* denote the optimal number of l that minimizes the mean square error between $\rho_{\max}(BP)$ and $\rho_{\max}(IC_l)$ as follows:

$$l^* = \arg\min_{l=1,2,\ldots,n} E[\{\rho_{\max}(BP) - \rho_{\max}(IC_l)\}] \quad (4).$$

Let j^* denote the optimal number of l that minimizes the mean square error between $\rho_{\max}(Ev)$ and $\rho_{\max}(IC_l)$ as follows:

$$j^* = \arg\min_{l=1,2,\ldots,n} E[\{\rho_{\max}(Ev) - \rho_{\max}(IC_l)\}] \quad (5)$$

where $\rho_{\max}(Ev)$ represents an event signal in the Valsalva maneuver. $\rho_{\max}(Ev)$ is defined as follows:

$$\rho_{\max}(Ev) = \begin{cases} 0 & \text{(Valsalva maneuver)} \\ 1 & \text{(resting condition)} \end{cases} \quad (6).$$

Applying the same $\boldsymbol{A}^+$ as obtained above to the data measured in Experiment II (presentation of a swaying video image) yields another IC_l. Let $l = l^*$ in this IC_l, and then IC_{l*} means the independent component time series closest to blood pressure variability BP in the meaning of (4) based on the data of Experiment I. Let $\rho_{\max}(IC_{l*})$ denote $\rho_{\max}$ between HR and IC_{l*}. In addition, Let $l = j^*$ in this IC_l, and then IC_{j*} means the independent component time series closest to the event signal $\rho_{\max}(Ev)$ in the meaning of (5) based on the data of Experiment I. Let $\rho_{\max}(IC_{j*})$ denote $\rho_{\max}$ between HR and IC_{j*}. $\rho_{\max}(IC_{j*})$ can be obtained without BP information. In the same way, $\rho_{\max}(BP)$ was also calculated for the data measured in Experiment II.

Results and Discussion

Experiment I (Valsalva maneuver). In Experiment I, all the 15 subjects' data could be obtained and analyzed successfully. Figure 5 shows the changes in $\rho_{max}(BP)$, $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ with time. Each ρ_{max} is the averaged value over the 15 subjects and the standard deviation (S.D.) is shown in the lower part of the figure.

These results revealed that $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ varied similarly to $\rho_{max}(BP)$ with time. Note that $\rho_{max}(IC_{j^*})$ which was calculated without *BP* information was similar to $\rho_{max}(BP)$.

Experiment II (presentation of the swaying video image). Fourteen subjects' data out of 15 could be successfully obtained in Experiment II. From the result of the subjective evaluation based on the SSQ, the median of *TS* of the 14 subjects was 17.7. All subjects were divided into two groups: Sick group and Well group. Sick group consists of 7 subjects with *TS* higher than 17.7 and Well group consists of 7 subjects with *TS* lower than 17.7.

Figure 6 shows the changes in $\rho_{max}(BP)$, $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ in Experiment II. Each ρ_{max} was averaged over the 14 subjects. In this figure, $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ changed similarly to $\rho_{max}(BP)$ although $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ were calculated from the mixing matrix ***A*** obtained from Experiment I. This result suggests that ***A*** obtained in an experiment is still valid for the other experiment. However, the changes in $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ did not completely correspond that of $\rho_{max}(BP)$. This result means that the responses of *BP* and the PPG to the Valsalva maneuver caused by the autonomic nervous activity are not always equivalent to the responses to the swaying video image.

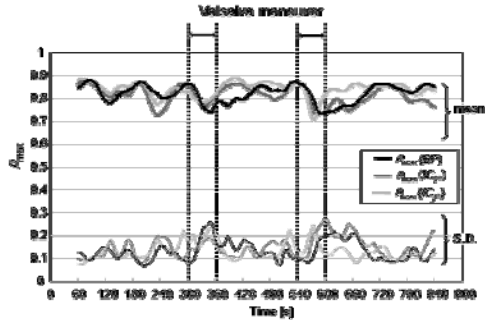

Figure 5. Changes in ρ_{max} in Experiment I (Valsalva maneuver). Each ρ_{max} was averaged over 15 subjects. $\rho_{max}(IC_{l^*})$ was chosen so as to minimize the mean square error between $\rho_{max}(BP)$ and $\rho_{max}(IC_l)$.

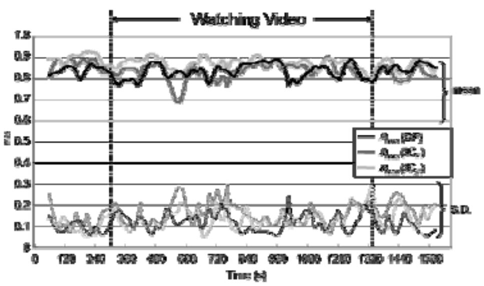

Figure 6. Changes in ρ_{max} in Experiment II (presentation of the swaying video image). Each ρ_{max} was averaged over 14 subjects. $\rho_{max}(IC_{l^*})$ was calculated from the same mixing matrix as obtained in Experiment I.

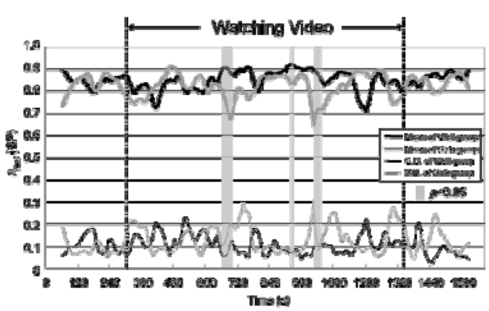

Figure 7. Comparison in ρ_{max} using *BP* between Sick and Well groups in Experiment II.

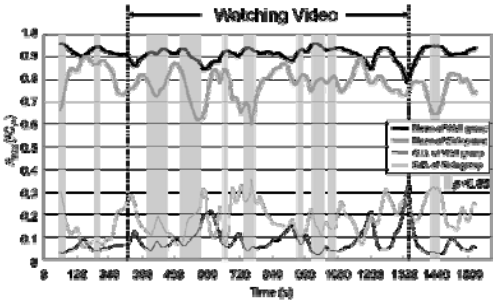

Figure 8. Comparison in ρ_{max} using IC_{l*} between Sick and Well groups in Experiment II.

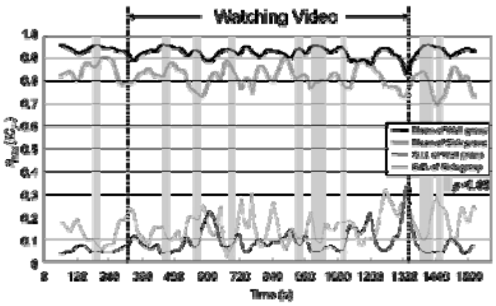

Figure 9. Comparison in ρ_{max} using IC_{j*} between Sick and Well groups in Experiment II.

Figures 7, 8 and 9 show the changes of $\rho_{max}(BP)$, $\rho_{max}(IC_{l*})$ and $\rho_{max}(IC_{j*})$ averaged over 14 subjects, respectively. In these figures, each ρ_{max} was compared between Sick and Well groups. The shadow shown in these figures represents the time interval in which the significant difference (p<0.05) between two groups was found by the Welch's t-test.

These results show that $\rho_{max}(BP)$, $\rho_{max}(IC_{l*})$ and $\rho_{max}(IC_{j*})$ of Sick group were significantly lower than those of Well group within the presentation of the video image. This fact suggests that the decrease in $\rho_{max}(BP)$, $\rho_{max}(IC_{l*})$ or $\rho_{max}(IC_{j*})$ reflects the symptoms of VIMS caused by watching the swaying video image. The significant difference in $\rho_{max}(BP)$ between Sick and Well groups shown in Fig.7 implies that the effect of VIMS was strong especially at around 720s and 960s. On the other hand, the frequent significant difference found in Fig.8 and Fig.9 indicates that $\rho_{max}(IC_{l*})$ and $\rho_{max}(IC_{j*})$ are more sensitive to the effect of VIMS than $\rho_{max}(BP)$. In particular, $\rho_{max}(IC_{l*})$ is more sensitive than other indices. So, ρ_{max} of Sick group in the result of experiment with Valsalva maneuver was compared with that of Well group.

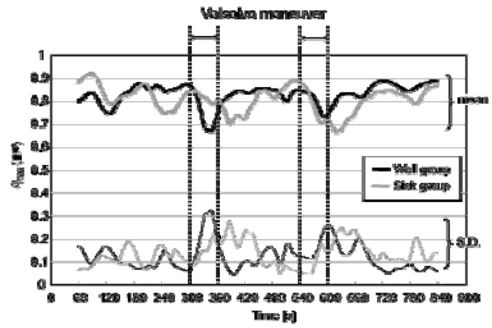

Figure 10. Comparison in ρ_{max} using BP between Sick and Well groups in Experiment I.

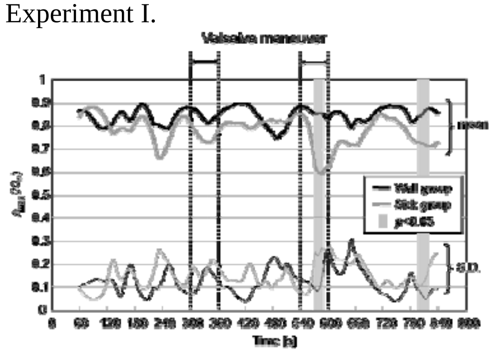

Figure 11. Comparison in ρ_{max} using IC_{l*} between Sick and Well groups in Experiment I.

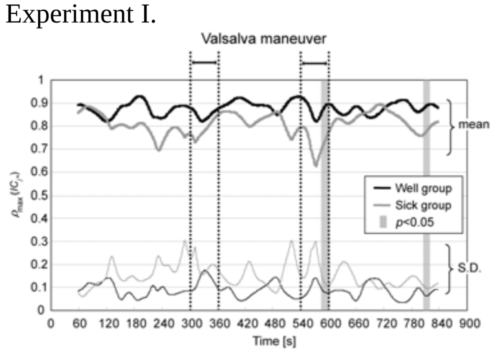

Figure 12. Comparison in ρ_{max} using IC_{j*} between Sick and Well groups in Experiment I.

Figures 10, 11 and 12 show the changes in $\rho_{max}(BP)$, $\rho_{max}(IC_{l*})$ and $\rho_{max}(IC_{j*})$ averaged over 14 subjects, respectively. In these figures, each ρ_{max} was compared between Sick and Well groups in Experiment I. Figure 10 shows that there was no significant difference between $\rho_{max}(BP)$ of Sick group and that of Well group. However, $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ of Sick group were significantly lower than those of Well group within the second part of Valsalva maneuver. Therefore, new kinds of ρ_{max} can reflect the autonomic nervous activity of a subject more sensitively than traditional ρ_{max} using BP. In addition, there is a possibility that we can see whether a subject suffers from VIMS or not by using $\rho_{max}(IC_{l^*})$ and $\rho_{max}(IC_{j^*})$ obtained from the result of the Valsalva maneuver.

Conclusions

To quantify the effect of VIMS, this study has proposed a new method for extracting a blood pressure-related parameter and an event-related parameter from finger photoplethysmography using the independent component analysis. From the experimental results, it was ascertained that the proposed method could extract the independent component related to blood pressure and to the event signal to yield the maximum cross-correlation coefficient ρ_{max} between heart rate and the independent component used for judging the symptoms of VIMS. It was also shown that new kinds of ρ_{max} based on the independent component extracted from photoplethysmography was more sensitive to VIMS rather than the conventional ρ_{max} based on blood pressure. Furthermore, ρ_{max} based on independent component related to the event can be obtained without blood pressure measurement.

However, the number of independent components and feature variables are needed to ensure whether the proposed number was optimal or not. In the future, we should develop a method for deciding the mixing matrix with photoplethysmography only using other mathematical theory or calculation algorithm for independent component analysis.

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