Quantitative Evaluation of Effects of Visually-Induced Motion Sickness Based on Causal Coherence Functions between Blood Pressure and Heart Rate

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Keywords: blood pressure, heart rate, visually-induced motion sickness, causal coherence function.

Abstract. To evaluate the effect of VIMS, the present study has analyzed the linearity of the baroreflex system and that of the mechanical hemodynamic system by using causal coherence functions. The causal coherence functions have a capability of calculating linear correlation between two systems independently even if the systems are connected with each other to compose a closed-loop system. In the experiment, 56 healthy human subjects' heart rate and continuous blood pressure variability were measured to obtain the causal coherence functions when they were watching an unstable video image. The results showed that there were significant differences in the causal coherence functions as well as the traditional coherence function between the subjects who felt VIMS and those who did not, and that the hemodynamic system was mainly disturbed by VIMS rather than the baroreflex system. These findings suggest that the causal coherence functions of the two systems and the traditional coherence function of the whole system gave different information from one another. This fact implies that the causal coherence functions will be useful and can be objective means to quantify VIMS.

Introduction

Recently, display device technology has rapidly developed and people have become exposed to new types of display systems such as widescreen TV sets with high resolution and deep contrast. In addition, progress of video and CG technology has made possible the creation of novel images including complex and intensive motion of visual point which traditional camera techniques cannot realize physically.

However, adverse effects of visual stimulation on humans have not sufficiently been ascertained (Nakagawa *et al.*, 1998). Pokemon incident arose in 1997 in Japan sounded the alarm about the risk of a particular kind of visual stimulation such as an image including flashing light (Harding, 1998). Furthermore, at a junior high school

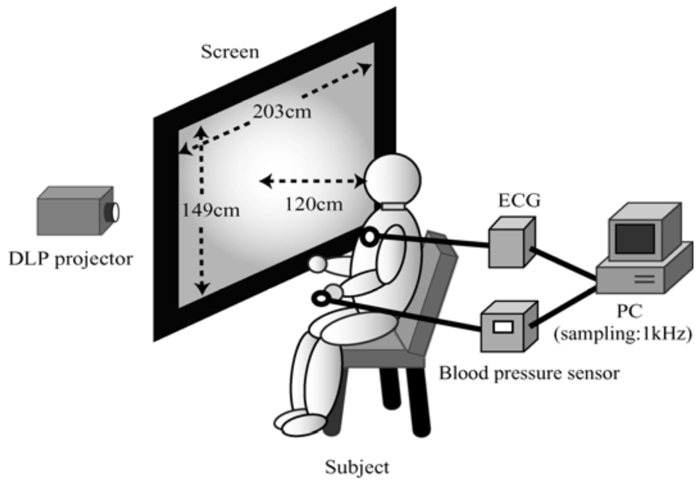

Figure 1. Schematic illustration of the experiment.

in Japan in 2003, there was the incident that 36 students out of 294 complained visually-induced motion sickness (VIMS) in watching a video image taken by an amateur camera man with a unstable handy camera.

In such situations, it is necessary to evaluate how seriously a viewer suffers from VIMS. For this problem, many studies have reported about subjective methods for evaluating VIMS (Kennedy *et al.*, 1993). However, adequate studies have not done yet on quantitative and objective methods using biological parameters. In the previous work, the authors focused on the correlation between blood pressure and heart rate variability to evaluate the effects of VIMS, that is to say, baroreflex function (Sugita *et al.*, 2002). The index we proposed is considered to reflect the autonomic nervous activity and decreased when human subjects felt VIMS strongly. However, the index we proposed cannot consider the causality of the cardiovascular system. In other words, we should analyze both the baroreflex and the mechanical paths independently, these paths form a cardiovascular system. And it is important to know which path is more affected by the biological reaction to the stimulation for understanding the mechanism of biological effects of VIMS more in detail.

The purpose of this study is to find quantitative indices that can represent the effect of VIMS in terms of the autonomic nervous activities. Especially in this study, causal coherence functions (Porta *et al.*, 2002) were introduced. They can derive the strength of the causal coupling on both arms of the cardiovascular system regarded as a closed-loop system.

Methods

Experiment. Figure 1 shows the schematic illustration of our experiment.

In the experiment, a video image clipped from a film was used as a visual stimulation shown to human subjects. The film is notorious for inducing VIMS because it was taken by an intentionally unstable handy camera to enhance reality in spite of a fiction. The video image clipped from the film contains no violent scene. The video image was projected from back side of a fiction. The video image clipped from the film contains no violent scene. The video image was projected from back side of a screen by a DLP projector (resolution: 1024x768, brightness: 800ANSI lumens).

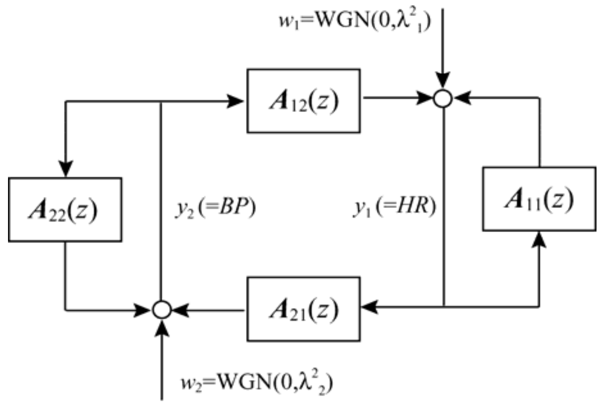

Figure 2. Closed-loop bivariate autoregressive model for the cardiovascular system. $WGN(0,\lambda_i^2;\ i=1,2)$ shows white Gaussian noise with zero mean and variance of λ_i^2.

The total number of subjects was 56 (34 males and 22 females; aged 18 to 35; mean age: 22.8) and the informed consent was obtained from all of them. They were told to watch consist of the series of images as follows: 1) a 3 min-long still picture of a landscape for a control; 2) the 15 min-long video image described above; 3) the same 3 min-long still picture as step 1. Before the trial, the subject answered questionnaires about his or her physical and mental state. After watching the video image, the subject was charged Simulator Sickness Questionnaire (SSQ) (Kennedy *et al.*, 1993). This SSQ contains 16 items to check the subject's physical disorder. The subject rated the degree of these items in 4 levels. Three subscales, i.e., nausea, oculomotor and disorientation, were calculated based on results of 16 items, and total score was calculated with these subscales.

During the trial, ECG and continuous blood pressure were measured by an ECG amp (ECG100C; BIOPAC System Inc.) and a finger-tip blood pressure sensor (PORTAPRES; Finapres Inc.), respectively. These signals were stored in a personal computer every 1ms. Heart rate (*HR*) was calculated from the reciprocal of the inter-R-wave interval of the ECG signal. Systolic blood pressure (*SBP*) was obtained as the maximum value of the pressure signal over one heartbeat.

Analysis. First, the beat-to-beat variables *HR* and *SBP* were interpolated by the cubic spline function, and they were re-sampled every Δt = 0.5s to yield time discrete variables $HR(k)$ and $SBP(k)$; k=1, 2, 3, …, respectively.

Not only coherence function $K^2(f)$ but also two causal coherence functions $K^2_{\mathrm{SBP}\to\mathrm{HR}}(f)$ and $K^2_{\mathrm{HR}\to\mathrm{SBP}}(f)$ were calculated on the basis of the bivariate autoregressive (AR) model shown in Fig.2 (Porta *et al.*, 2002). Let $y_1(k)$ and $y_2(k)$ denote $HR(k)$ and $SBP(k)$ respectively, then the power spectra ($S_{11}(f)$ and $S_{22}(f)$) of $y_1(k)=HR(k)$ and $y_2(k)=SBP(k)$ are given by

$$S_{11}(f)=|\Delta(z)|^2\cdot\left[\,|1-A_{22}(z)|^2\cdot\lambda_1^2+|A_{12}(z)|^2\cdot\lambda_2^2\right]\Big|_{z=e^{j2\pi f\Delta t}} \quad (1)$$

$$S_{22}(f)=|\Delta(z)|^2\cdot\left[\,|A_{21}(z)|^2\cdot\lambda_1^2+|1-A_{11}(z)|^2\cdot\lambda_2^2\right]\Big|_{z=e^{j2\pi f\Delta t}} \quad (2)$$

while the cross-spectrum ($S_{12}(f)$) from *HR* to *SBP* is given by

$$S_{12}(f)=|\Delta(z)|^2\cdot\Big[(1-A_{22}(z))\cdot A_{21}(z^{-1})\cdot\lambda_1^2 + A_{12}(z)\cdot(1-A_{11}(z^{-1}))\cdot\lambda_2^2\Big]\Big|_{z=e^{j2\pi f\Delta t}} \quad (3)$$

where $\Delta(z)=[\{1-A_{11}(z)\}\{1-A_{22}(z)\}-A_{12}(z)A_{21}(z)]^{-1}$. The AR parameters were identified via the least-squares method.

The squared coherence function between $HR(k)$ and $SBP(k)$ is defined as follows:

$$K^2(f) = \frac{|S_{12}(f)|^2}{S_{11}(f) \cdot S_{22}(f)} \qquad (4)$$

The index $K^2(f)$ represents the whole linearity of the system shown in Fig.2. Here, if one of the AR parameters which represent the strength of the causal coupling is set to zero virtually, the linearity of the each arm in the closed-loop is defined as follows:

$$K^2{}_{HR\rightarrow SBP}(f) = K^2(f)\Big|_{A_{12}(z)=0} \qquad (5)$$

$$K^2{}_{SBP\rightarrow HR}(f) = K^2(f)\Big|_{A_{21}(z)=0} \qquad (6)$$

These $K^2{}_{\mathrm{SBP}\rightarrow\mathrm{HR}}(f)$ and $K^2{}_{\mathrm{HR}\rightarrow\mathrm{SBP}}(f)$ are causal coherence functions and correspond to the neural baroreflex system and the mechanical hemodynamics in the cardiovascular system, respectively.

The mean values of $K^2(f)$, $K^2{}_{\mathrm{SBP}\rightarrow\mathrm{HR}}(f)$ and $K^2{}_{\mathrm{HR}\rightarrow\mathrm{SBP}}(f)$ at the Mayer wave-band (0.05Hz < f < 0.15Hz) were calculated time-discretely every 10s on the basis of the last 2min-long data. Thus these coherence functions can be plotted as functions of time.

Results

All subjects were classified into three groups based on total score of SSQ.

Top 18 subjects with high total score felt into Sick group, bottom 18 subjects with low score felt into Well group, and the other 20 subjects felt into Neutral group.

Figure 3 shows the mean time trajectories of a) K^2, b) $K^2{}_{\mathrm{SBP}\rightarrow\mathrm{HR}}$ and c) $K^2{}_{\mathrm{HR}\rightarrow\mathrm{SBP}}$ compared between Sick and Well groups. The shadow depicted in the figure represents the time period in which there was a significant difference between the two groups for more than two consecutive points (more than 20s). The significant test was followed by Welch's t-test with a 5% significant level.

In this figure, all three kinds of coherence functions of Sick group were lower than those of Well group at many points of time and these differences were significant at some points of time in watching the video. The significant difference in K^2 and $K^2{}_{\mathrm{HR}\rightarrow\mathrm{SBP}}$ were observed at the latter part of the video (after t=800s). On the other hand, that in $K^2{}_{\mathrm{SBP}\rightarrow\mathrm{HR}}$ was observed at the middle part of the video (around t=480s).

Discussion

Low linearity in the cardiovascular system implies that heart rate varies independently of blood pressure and/or blood pressure varies independently of heart rate. Figure 3 suggests that the linearity of the Sick group tends to be lower than that of the Well group. Especially at around t=900s, there were significant differences both in K^2 and $K^2{}_{\mathrm{HR}\rightarrow\mathrm{SBP}}$ between the two groups while $K^2{}_{\mathrm{SBP}\rightarrow\mathrm{HR}}$ had little difference. This means that blood pressure tended to change independently of heart rate in the Sick group. Such situation may happen when blood pressure is mainly determined by the peripheral vascular resistance rather than by heart rate. As well as heart rate, the peripheral vascular resistance is manipulated by the autonomic nervous system to regulate blood pressure. Consequently, it seems that the subjects in the Sick group suffered from VIMS by watching the unstable video image, and then, their vasomotor activity controlled by the autonomic nervous system was disturbed to decrease K^2 and $K^2{}_{\mathrm{HR}\rightarrow\mathrm{SBP}}$.

Previous studies (Lo *et al.*, 2001; Ohmi *et al.*, 2004) reported that nausea scores obtained from subjects watching a unstable visual image for 5min or so were not high. This agrees with our results that the differences in K^2 and $K^2{}_{\mathrm{HR}\rightarrow\mathrm{SBP}}$ between Sick and Well groups shown in Fig.3 became significantly wider after a lapse of about 10min from the beginning the video. On the other hand, as shown in Fig.3b), a significant difference in $K^2{}_{\mathrm{SBP}\rightarrow\mathrm{HR}}$ between

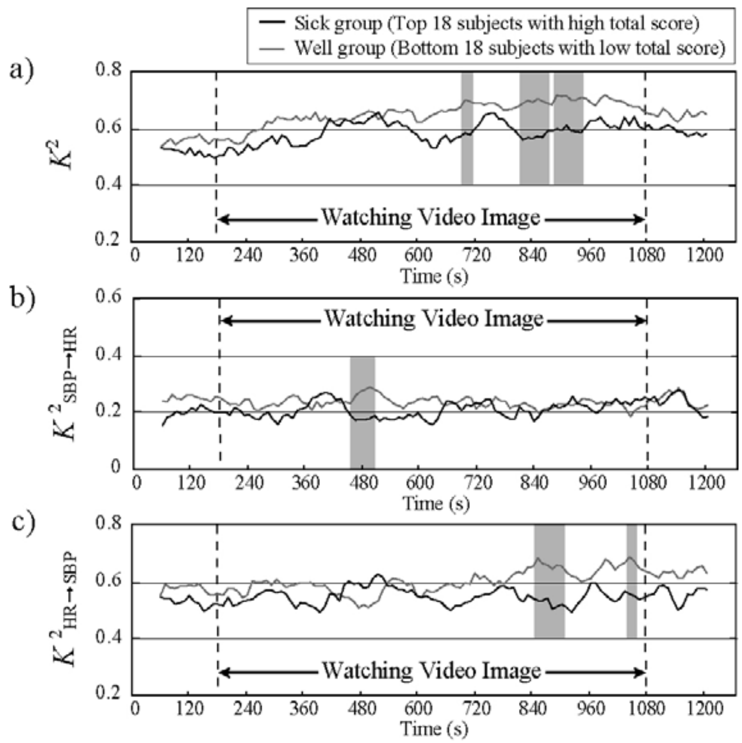

Figure 3. Changes in a) K^2, b) $K^2_{SBP\to HR}$ and c) $K^2_{HR\to SBP}$ with time in the low frequency band (0.05-0.15Hz). In each figure, Sick group (top 18 subjects with high total score) and Well group (bottom 18 subjects with low total score) are compared with each other. The shadow in the figure represents the time period in which there was a significant difference for more than two points (more than 20s) between the two groups.

the two groups was observed before 10min. Yoshino reported that the mean value of $K^2_{SBP\to HR}$ during acute restraint stress was significantly lower than during the baseline period (Yoshino *et al.*, 2005). In our earlier study, a subject who is prone to motion sickness had a tendency that his physiological index changed immediately after the beginning of the presentation of the unstable video (Sugita *et al.*, 2004). This change may be not exactly caused by VIMS but by an emotional or psychological reaction in which he or she reflexively felt repulsive to avoid seeing such an uncomfortable video. This suggests that the proposed indices cannot distinguish the physiological symptoms of VIMS from the psychological reactions. However, the emotional or psychological reactions must be correlated with VIMS such that the reactions may have a significant difference between the two groups. Consequently, it is possible that there was a factor for giving the subjects mental stress at this point of time in the video, and this mental stress may be linked to symptom onset of VIMS, in other words, this may be a triggering phenomenon of VIMS.

Conclusion

To evaluate the effect of VIMS on humans, the correlation between blood pressure and heart rate variability of 56 healthy subjects watching an unstable video image were analyzed by using not only a traditional coherence function but also two causal coherence functions. The experimental results have shown that there were significant differences both in traditional and causal coherence functions between Sick and Well groups. And causal coherence functions gave different information from the traditional coherence function with respect to the whole closed-loop system, thus causal coherence functions will be useful for understanding the mechanism of VIMS in terms of the autonomic nervous activity.

In future studies, we should check the effect of respiration pattern on our analysis because it was reported that the change in instantaneous lung volume gives not negligible effect on the activity of the cardiovascular system even if the frequency range of interest is not so high as frequency of respiratory sinus arrhythmia (Mullen *et al.*, 1997). Furthermore, we should improve the method by using multiple parameters and analyze data from more subjects to confirm the validity of the proposed method.

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