BIORESPONSE TO STEREOSCOPIC MOVIES PRESENTED VIA A HEAD-MOUNTED DISPLAY

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Abstract: Three-dimensional (3-D) television sets are already available in the market and are becoming increasingly popular among consumers. The 3-D movies they play, however, induce the negative sensations of asthenopia and motion sickness in some viewers. Visually induced motion sickness (VIMS) is caused by sensory conflict, i.e., a disagreement between vergence and visual accommodation during the viewing of stereoscopic images. VIMS can be analyzed both subjectively and physiologically. The objective of this study is to develop a method for detecting VIMS. We quantitatively measured head acceleration and body sway during viewer exposure to both a two-dimensional (2-D) image and a conventional three-dimensional (3-D) movie. The subjects wore head-mounted displays (HMDs) and maintained the Romberg posture for the first 60 s and a wide stance (midlines of the heels 20 cm apart) for the next 60 s. Head acceleration was measured using an active tracer at a sampling frequency of 50 Hz. Subjects completed the Simulator Sickness Questionnaire (SSQ) immediately afterwards. Statistical analysis was then applied to the SSQ subscores and to each index of stabilograms. Transfer function analysis indicated that the acceleration of the head in the anterior-posterior direction while watching a 3-D movie can affect lateral body sway, thereby causing VIMS.

1 INTRODUCTION

Three-dimensional (3-D) television sets are already available in the market and are becoming increasingly popular among consumers. The 3-D movies they play, however, induce the negative sensations of asthenopia and motion sickness in some viewers. Although the most widely known theory of motion sickness is based on the concept of sensory conflict (Reson, 1978), Riccio and Stoffregen (1991) argued that motion sickness is caused not by sensory conflict, but by postural instability.

The equilibrium function in humans deteriorates during the viewing of 3-D movies (Takada et al., 2007). This visually induced motion sickness (VIMS) has been considered to be caused by a disagreement between vergence and visual accommodation during the viewing of 3-D images. VIMS can be measured using psychological and physiological methods; among these, the Simulator Sickness Questionnaire (SSQ) is a well-known psychological approach to measuring the extent of motion sickness (Kennedy et al., 1993). In this study, the SSQ is used for verifying the occurrence of VIMS. The following parameters of autonomic nervous activity are appropriate for a physiological assessment: heart rate variability, blood pressure, body sway, electrogastrography, and galvanic skin reaction (Holomes and Griffin, 2001). A wide stance (with the midlines of the heels 17–30 cm apart) reportedly results in a significant increase in the total locus length in stabilograms for individuals with high SSQ scores, while the length in those of individuals with low scores is less affected by such a stance (Scibora et al., 2007).

Mathematically, the sway in the center of pressure (COP) is described as a stochastic process (Collons and De Luca, 1993, and Emmerrik et al., 1993). The anterior-posterior (y) direction was

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considered to be independent of the medial-lateral (*x*) direction (Goldie et al., 1989). The following stochastic differential equations (SDEs) on the Euclid space $\mathbf{E}^2 \ni (x, y)$ have been proposed as mathematical models that can generate stabilograms.

$$\frac{\partial x}{\partial t} = -\frac{\partial}{\partial x} U_x(x) + w_x(t)\,, \qquad (1.1)$$

$$\frac{\partial y}{\partial t} = -\frac{\partial}{\partial y} U_y(y) + w_y(t)\,, \qquad (1.2)$$

where $w_x(t)$ and $w_y(t)$ express white noise terms. We examined the adequacy of using an SDE and investigated the most adequate equation for our research. G(x), the distribution of the observed point x, is related to V(x), the (temporal averaged) potential function in the SDE, which has been considered as a mathematical model of swaying, in the following way:

$$V(\vec{x}) = -\frac{1}{2}\ln G(\vec{x}) + const. \qquad (2)$$

The nonlinear property of SDEs is important (Takada et al., 2001). There were several minimal points of the potential. In the vicinity of these points, local stable movement with a high-frequency component can be generated as a numerical solution of the SDE. We can therefore expect a high density of observed COP in this area on the stabilogram.

Using the SSQ and stabilometry, in this study we examined whether VIMS is in fact induced by a stereoscopic movie. We wondered if noise terms vanished from the mathematical model (SDEs) of body sway. Using our Double-Wayland algorithm (Takada et al., 2006), we evaluated the degree of visible determinism of the dynamics of body sway. We also investigated the relationship between body sway and head acceleration by performing transfer function analysis.

The correlation between head movement and the movement of the center of gravity has been investigated in general, and a corporative effect was found in their relationship (Sakaguchi et al., 1995). By showing a stereoscopic movie to subjects, Takeda et al. verified that there is a corporative correlation between head movement and body sway (Takeda et al., 1995). We herein assume that the input signal, x(t), is the head acceleration in the transfer system to control body sway, as shown in Figure 1. In this figure, we denote the Fourier transform by a capital letter that corresponds to the letter of the function being transformed (such as y(t) and Y(f)). The transfer function H(f) is defined as a Fourier transform of the impulse response h(f). In our experiments, we cannot observe the output signal of the transfer system; only the signal added to the noise n(t) can be observed. Based on the following theorem (Winner-Khinchine)

$$W_{xx} = |X(f)|^2 = \sigma_x^{\,2}\,\mathcal{F}(R_{xx}), \qquad (3)$$

we can easily estimate a power spectrum W_{xx}. On the right-hand side of Equation (3), σ_x expresses the standard deviation and $\mathcal{F}(R_{xx})$ indicates the Fourier transform of the autocorrelation function with respect to the signal x(t). In this study, we estimate the transfer function that controls body sway.

We also examine whether the motion sickness induced by 3-D images affected body sway and head acceleration and the changes in the control system.

2 MATERIALS AND METHODS

Ten healthy subjects (age: 23.6 ± 2.2 years) voluntarily participated in this study, and each of them provided informed consent prior to participation.

We ensured that the subjects' body sway was not affected by environmental conditions. With an air conditioner, we were able to maintain the room temperature at 25 °C. We also kept the room dark. The subjects wore a head-mounted display (HMD; iWear AV920; Vuzix Co. Ltd.) on which 2 kinds of images were presented in a random order: (I) a static visual target (circle) with a diameter of 3 cm; and (II) a conventional 3-D movie that showed a sphere that approaches and moves away from the subject with irregular movement.

Before the subjects' body sway was recorded, the subjects stood still on the detection stand of a stabilometer (G5500; Anima Co. Ltd.) in the Romberg posture with their feet together for 1 min. Each sway of the COP was then recorded at a sampling frequency of 20 Hz during measurements, while head acceleration was simultaneously recorded by an active tracer (AC-301A; GMS Co. Ltd.) at 50 Hz. Subjects were instructed to maintain the Romberg posture for the first 60 s and a wide stance (with the midlines of their heels 20 cm apart) for the next 60 s. The subjects viewed one of the images, i.e., (I) or (II), on the HMD from the beginning until the end. The SSQ was filled out both before and after stabilometry testing.

We calculated several indices that are commonly used in the clinical field (Suzuki et al., 1996) for stabilograms, such as "area of sway," "total locus length," and "total locus length per unit area." In addition, new quantification indices that were termed "sparse density" (SPD), "total locus length of chain" (Takada et al., 2003), and "translation error" were also estimated.

When subjects stood with their feet close together (Romberg posture), the coherence function between the head acceleration x(i) and the movement of the centre of gravity y(j) was estimated as

$$coh_{x(i)y(j)}(f) = |W_{x(i)y(j)}|^2/(W_{x(i)x(i)}\ W_{y(j)y(j)}), \qquad (4)$$

where i and j express the component (1: lateral, 2: anterior/posterior). By using the Fast Fourier transform algorithm, power spectrums $W_{x(i)x(i)}$, $W_{y(j)y(j)}$ were estimated. On the basis of Equation (4), we calculated cross spectrums $W_{x(i)y(j)}$. Coherence indicates an index for the degree of linear correlation between input and output signals ($0 \leq coh \leq 1$). There is a completely linear correlation between these signals when coh = 1. In this study, we assumed that a linear system intervenes between the head and the body sway only if $coh \geq 0.12$ (a significant correlation coefficient for N = 512, $p < 0.01$).

3 RESULTS

After subjects were exposed to a conventional 3-D movie (II), the scores for SSQ-N (nausea), SSQ-OD (eyestrain), SSQ-D (disorientation), and SSQ-TS (total score) were 11.4 ± 3.7, 18.2 ± 4.1, 23.7 ± 8.8, and 19.8 ± 5.3, respectively. Symptoms of sickness seemed to appear with exposure to the stereoscopic images, albeit with large individual differences.

The amplitudes of body sway that were observed during the exposure to the movie tended to be larger than those of the control sway. Although a high density of COP was observed in the stabilograms for the resting state (I), the density decreased during exposure to a conventional stereoscopic movie (II). Furthermore, stabilograms measured with subjects' feet wide apart were compared with those when they assumed the Romberg posture. The COP was not isotropically dispersed, but was characterized by considerable movement in the anterior-posterior (y) direction. The diffusion of COP was larger in the lateral (x) direction and had spread to the extent that it was equivalent to the stabilograms for the resting state.

According to the two-way analysis of variance (ANOVA) with repeated measurements, there was no correlation between the factors of posture (Romberg posture or standing posture with feet wide apart) and images (I or II). For the total locus length, area of body sway, and SPD, the main effects were in response to both factors ($p < 0.01$). Multiple comparisons revealed that these indices significantly increased when the subjects viewed the 3-D movie (II) with their feet close together (Romberg posture). VIMS could be detected by these indices for the stabilograms. Whether or not the subjects were exposed to the 3-D movies, the value for E_{trans} derived from the temporal differences of those time series x, y was approximately 1 (Figure 1). These translation errors in each embedding space were not significantly different from the translation errors derived from the time series x, y.

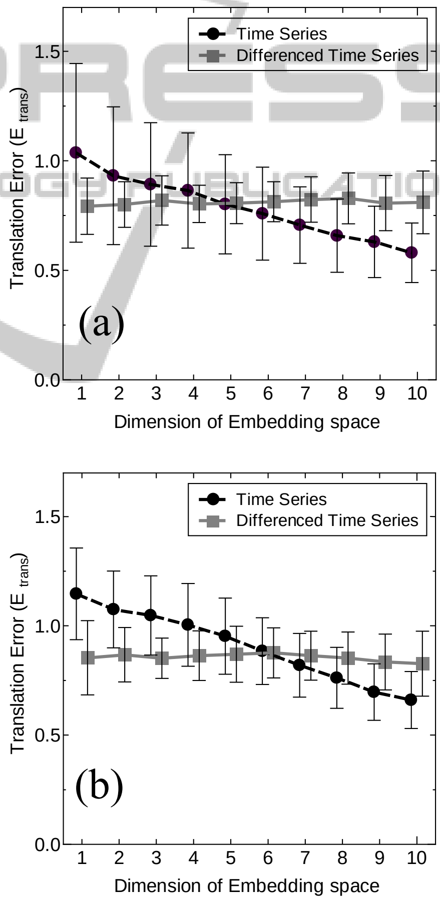

Figure 1: Mean translation error for each embedding space. Representative results of the Double-Wayland algorithm are derived from the lateral sway x. Translation errors were estimated from stabilograms that were observed when subjects viewed (a) a static circle and (b) a conventional 3-D movie.

When the subjects stood with their feet close together (Romberg posture), transfer function analysis was performed using the head acceleration (input) and the body sway (output). We estimated the coherence function (4), i.e., $coh_{x(1)y(1)}(f)$, $coh_{x(1)y(2)}(f)$, $coh_{x(2)y(1)}(f)$, and $coh_{x(2)y(2)}(f)$. For any frequency, $coh_{x(1)y(1)}(f)$ and $coh_{x(1)y(2)}(f)$ were less than 0.12 (a significant correlation coefficient for N = 512, p < 0.01). On the other hand, $coh_{x(2)y(2)}(0.51)$ was more than 0.12. $coh_{x(2)y(j)}(0.51)$ and $coh_{x(2)y(j)}(7)$ were remarkably augmented by exposure to the 3-D movie (II) for j = 1, 2.

4 DISCUSSION

A theory has been proposed regarding how to obtain SDEs as a mathematical model of body sway on the basis of a stabilogram. Multiple comparisons indicated that the SPD S_2 during exposure to the stereoscopic movie was significantly larger than that during exposure to the static control image (I) when subjects stood in the Romberg posture. The same calculation results were also obtained for S_3. The standing posture would become unstable due to the effects of the stereoscopic movie. As mentioned above, structural changes occur in the time-averaged potential function (2) upon exposure to stereoscopic images, which are assumed to reflect the sway in the center of gravity. While subjects watch the 3-D movie, their lateral sway might become dependent on its transverse component in the head movement.

Scibora et al. (2007) concluded that the total locus length of subjects with prior experience of motion sickness increased with exposure to a virtual environment when they stood with their feet wide apart, In our study, however, the degree of sway was found to be significantly less when the subjects stood with their feet wide apart than when they stood with their feet close together (Romberg posture). However, the total locus length during exposure to a conventional stereoscopic movie was significantly longer than that during exposure to the control image when they stood with their feet wide apart. As shown in Figure 4d, a clear change in the form of the potential function (1) occurs when the feet are wide apart.

Regardless of posture, the total locus length during exposure to the conventional 3-D movie (II) was significantly greater than that during exposure to the control image. Moreover, the total locus length of the chain tended to increase when subjects were exposed to conventional 3-D images (II), as compared to when they were exposed to (I). Hence, by using these indicators for the stabilogram (total locus length and that of chain), we were able to note postural instability associated with the exposure to conventional stereoscopic images (II).

In this study, the degree of determinism in the dynamics of the sway of the COP was mathematically measured. The Double-Wayland algorithm was used as a novel method. $E_{\mathrm{trans}} > 0.5$ was obtained by the Wayland algorithm (Figure 1), which implies that a time series could be generated by a stochastic process in accordance with a previous standard (Matsumoto et al., 2002). The threshold 0.5 is half of the translation error that results from a random walk. Body sway has been described previously in terms of stochastic processes (Collons and De Luca, 1993, Emmerrik et al., 1993, and Takada et al., 2001), which were demonstrated with the Double-Wayland algorithm (Takada et al., 2006). The translation errors estimated by the Wayland algorithm were similar to those obtained from the temporal differences. The exposure to 3-D movies would not change it into a deterministic one. Mechanical variations were not observed in the locomotion of the COP. It was assumed that the COP was controlled by a stationary process, and the sway during exposure to the static control image (I) could be compared with that when the subject viewed 3-D movies. The indices for stabilograms might reflect the coefficients in stochastic processes, though the translation error did not indicate a significant difference between the stabilograms measured during exposure to the static control image (I) versus to a conventional 3-D movie (II).

Constructing the nonlinear SDEs (1) from the stabilograms in accordance with Equation (2), we find that their temporally averaged potential functions U_x, U_y have plural minimal points, and fluctuations could be observed in the neighborhood of these minimal points (Takada et al., 2001). The variance in the stabilogram depends on the form of the potential function in the SDE; therefore, the SPD is regarded as an index for its measurement. The total locus length increased during the exposure to conventional 3-D images (II), a phenomenon that might be caused by the diminution of the gradient at the bottom of the potential function (Figure 2). We would note here that it is important to focus on the nonlinearity of the potential function. We have succeeded in estimating the decrease in the gradient of the potential function using the SPD by performing a one-way analysis of variance.

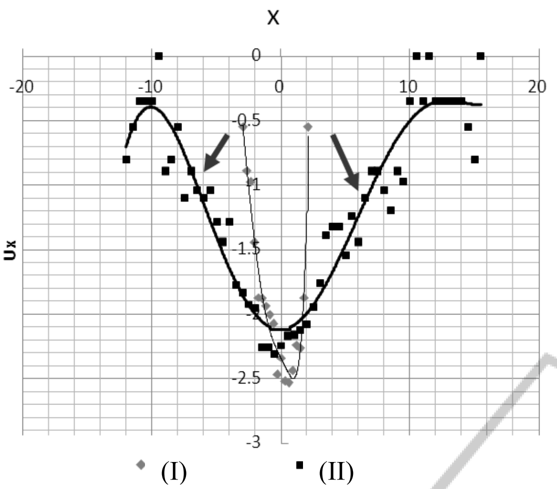

Figure 2: Metamorphosis of potential function. A clear change in the form of the potential function (2) occurs when the feet are wide apart.

5 CONCLUSIONS

It has been reported that visually induced motion sickness (VIMS) is caused by sensory conflict, e.g., the disagreement between vergence and visual accommodation while watching a 3-D movie. In this study, in order to evaluate VIMS, we simultaneously recorded the center of gravity and the head acceleration of subjects while they were exposed to a 2-D image or were watching a 3-D movie. The effect of VIMS in subjects who have a tolerance to motion sickness could be detected, especially by calculating the sparse density as an index of stabilograms.

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