Comparison in Degree of the Motion Sickness Induced by a 3-D Movie on an LCD and an HMD

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Abstract. Three-dimensional (3D) television sets are already on the market and are becoming increasingly popular among consumers. Watching stereoscopic 3D movies, though, can produce certain adverse affects such as asthenopia and motion sickness. Visually induced motion sickness (VIMS) is considered to be caused by an increase in visual-vestibular sensory conflict while viewing stereoscopic images. VIMS can be analyzed both psychologically and physiologically. According to our findings reported at the last HCI International conference, VIMS could be detected with the total locus length and sparse density, which were used as analytical indices of stabilograms. In the present study, we aim to analyze the severity of motion sickness induced by viewing conventional 3D movies on a liquid crystal display (LCD) compared to that induced by viewing these movies on a head-mounted display (HMD). We quantitatively measured the body sway in a resting state and during exposure to a conventional 3D movie on an LCD and HMD. Subjects maintained the Romberg posture during the recording of stabilograms at a sampling frequency of 20 Hz. The simulator sickness questionnaire (SSQ) was completed before and immediately after exposure. Statistical analyses were applied to the SSQ subscores and to the abovementioned indices (total locus length and sparse density) for the stabilograms. Friedman tests showed the main effects in the indices for the stabilograms. Multiple comparisons revealed that viewing the 3D movie on the HMD significantly affected the body sway, despite a large visual distance.

Keywords: visually induced motion sickness, stabilometry, sparse density, liquid crystal displays (LCDs), head-mounted displays (HMDs).

1 Introduction

The human standing posture is maintained by the body's balance function, which is an involuntary physiological adjustment mechanism called the "righting reflex" [1]. This righting reflex, which is centered in the nucleus ruber, is essential to maintain the standing posture when locomotion is absent. The body's balance function utilizes sensory signals such as visual, auditory, and vestibular inputs, as well as proprioceptive

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inputs from the skin, muscles, and joints [2]. The evaluation of this function is indispensable for diagnosing equilibrium disturbances like cerebellar degenerations, basal ganglia disorders, or Parkinson's disease [3].

Stabilometry has been employed for a qualitative and quantitative evaluation of this equilibrium function. A projection of a subject's center of gravity onto a detection stand is measured as an average of the center of pressure (COP) of both feet. The COP is traced for each time step, and the time series of the projections is traced on an x-y plane. By connecting the temporally vicinal points, a stabilogram is created, as shown in Fig. 1. Several parameters are widely used in clinical studies to quantify the degree of instability in the standing posture: for instance, the area of sway (A), total locus length (L), and locus length per unit area (L/A). It has been revealed that the last parameter is particularly related to the fine variations involved in posture control [1]. Thus, the L/A index is regarded as a gauge for evaluating the function of proprioceptive control of standing in human beings. However, it is difficult to clinically diagnose disorders of the balance function and identify the decline in equilibrium function by utilizing the abovementioned indices and measuring patterns in a stabilogram. Large interindividual differences might make it difficult to understand the results of such a comparison.

Mathematically, the sway in the COP is described by a stochastic process [4]–[6]. We examined the adequacy of using a stochastic differential equation (SDE) and investigated the most adequate equation for our research. G(x), the distribution of the observed point x, is related in the following manner to V(x), the (temporally averaged) potential function, in the SDE, which has been considered to be a mathematical model of sway:

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

The nonlinear property of SDEs is important [7]. There are several minimal points of potential. In the vicinity of these points, local stable movement with a high-frequency component can be generated as a numerical solution to the SDE. We can therefore expect a high density of observed COP in this area on the stabilogram.

The analysis of stabilograms is useful not only for medical diagnoses but also for achieving upright standing control in two-legged robots and preventing falls in elderly people [8]. Recent studies have suggested that maintaining postural stability is one of the major goals of animals, [9] and that they experience sickness symptoms in circumstances wherein they have not acquired strategies to maintain their balance [10]. Although the most widely known theory of motion sickness is based on the concept of sensory conflict [10]–[12], Riccio and Stoffregen [10] argued that motion sickness is instead caused by postural instability. Stoffregen and Smart (1999) reported that the onset of motion sickness may be preceded by significant increases in postural sway [13].

The equilibrium function in humans deteriorates when viewing 3-dimensional (3D) movies [14]. It has been considered that this visually induced motion sickness (VIMS) is caused by a disagreement between vergence and visual accommodation while viewing 3D images [15]. Thus, stereoscopic images have been devised to reduce this disagreement [16]–[17].

VIMS can be measured by psychological and physiological methods, and the simulator sickness questionnaire (SSQ) is a well-known psychological method for measuring the extent of motion sickness [18]. The SSQ is used in this study to verify the occurrence of VIMS. The following parameters of autonomic nervous activity are appropriate for the physiological method: heart rate variability, blood pressure, electrogastrography, and galvanic skin reaction [19]–[21]. It has been reported that a wide stance (with the midlines of the heels 17 or 30 cm apart) significantly increases the total locus length in the stabilograms of individuals with high SSQ scores, while the length for individuals with low scores is less affected by such a stance [22]. In our report at the last HCI International 2011, we reported that VIMS could be detected by the total locus length and sparse density, which were used as the analytical indices of stabilograms [23].

The objective of the present study is to compare the degree of motion sickness induced by viewing a conventional 3D movie on a liquid crystal display (LCD) with that from viewing a 3D movie on a head-mounted display (HMD). We quantitatively measured body sway during the resting state, exposure to a 3D movie on an LCD, and that on an HMD.

2 Material and Methods

Ten healthy subjects (age, 23.6 ± 2.2 years) voluntarily participated in the study. All of them were Japanese and lived in Nagoya and its surrounding areas. They provided informed consent prior to participation. The following subjects were excluded from the study: subjects working night shifts, those dependent on alcohol, those who consumed alcohol and caffeine-containing beverages after waking up and less than 2 h after meals, those using prescribed drugs, and those who may have had any otorhinolaryngologic or neurological disease in the past (except for conductive hearing impairment, which is commonly found in the elderly). In addition, the subjects had to have experienced motion sickness at some time during their lives.

We ensured that the body sway was not affected by environmental conditions. Using an air conditioner, we adjusted the temperature to 25 °C in the exercise room, which was kept dark. All the subjects were tested in this room from 10 a.m. to 5 p.m. Three kinds of stimuli were presented in random order: (I) a static circle with a diameter of 3 cm (resting state); (II) a conventional 3D movie that showed a sphere approaching and moving away from the subjects, irregularly; and (III) the same motion picture as shown in (II). Stimuli (I) and (II) were presented on an LCD monitor (S1911- SABK, NANAO Co., Ltd.). The distance between the LCD and the subjects was 57 cm. On the other hand, the subjects wore an HMD (iWear AV920; Vuzix Co. Ltd.) during exposure to the last movie (III). This wearable display is equivalent to a 62-inch screen viewed at a distance of 2.7 m.

The subjects stood without moving on the detection stand of a stabilometer (G5500; Anima Co. Ltd.) in the Romberg posture, with their feet together for 1 min before the sway was recorded. Each sway of the COP was then recorded at a sampling frequency of 20 Hz; the subjects were instructed to maintain the Romberg posture for the first 60 s. The subjects viewed one of the stimuli, that is, (I), (II), or (III), from the beginning till the end. They filled out an SSQ before and after the test.

We calculated several indices that are commonly used in the clinical field [24] for stabilograms, including the "area of sway," "total locus length," and "total locus length per unit area." In addition, new quantification indices that were termed SPD S_2, S_3, and total locus length of chain [25] were also estimated.

3 Results

The SSQ results are shown in Table 1 and include the nausea (N), oculomotor discomfort (OD), and disorientation (D) subscale scores, along with the total score (TS) of the SSQ. No statistical differences were seen in these scores among the stimuli presented to the subjects.

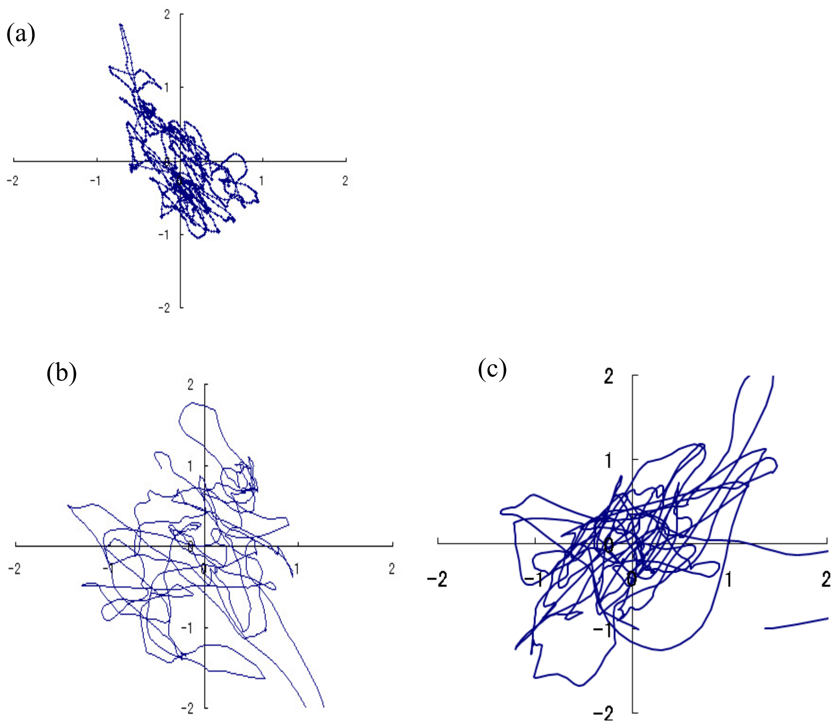

Fig. 1. Typical stabilograms observed when subjects viewed the static circle (a), the conventional 3D movie on the LCD (b), and the same 3D movie on the HMD (c).

Table 1. Table 1 Subscales of SSQ after exposure to 3D movies

Movies	(II)	(III)
N	14.3 ± 4.8	11.4 ± 3.7
OD	16.7 ± 4.0	18.2 ± 4.1
D	22.3 ± 9.3	23.7 ± 8.8
TS	19.8 ± 5.8	19.8 ± 5.3

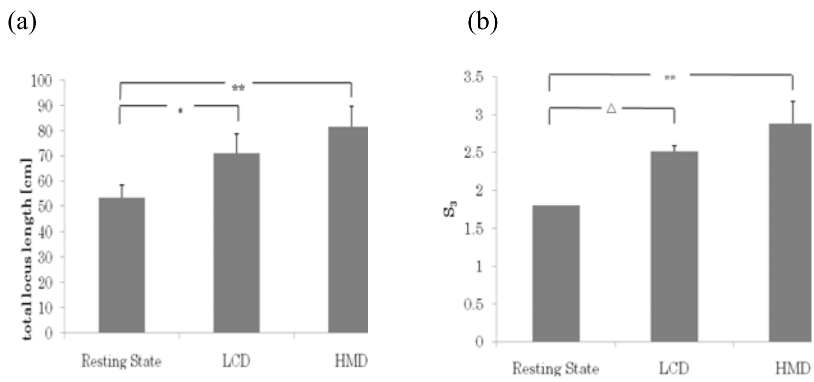

Fig. 2. Typical results of Nemenyi tests for the following indicators: total locus length (a) and SPD (b)

However, there were increases in the scores after exposure to the conventional 3D movies. Although there were large individual differences, sickness symptoms seemed to appear more often with the 3D movies.

Typical stabilograms are shown in Fig. 1. In these figures, the vertical axis shows the anterior and posterior movements of the COP, and the horizontal axis shows the right and left movements of the COP. The sway amplitudes that were observed during exposure to the movies (Fig. 1b–1c) tended to be larger than those of the control sway (Fig. 1a). Although a high COP density was observed in the stabilograms (Fig. 1a), this density decreased during exposure to the movies (Fig. 1b–1c).

According to the Friedman test, the main effects were seen in the indices of the stabilograms, except for the chain ($p < 0.01$). Nemenyi tests were employed as a post-hoc procedure after the Friedman test (Fig. 2). Five of the six indices were enhanced significantly by exposure to the 3D movie on the HMD ($p < 0.05$). Except for the total locus length, there was no significant difference between the values of the indices measured during the resting state and exposure to the 3D movie on the LCD ($p < 0.05$).

4 Discussion

A theory has been proposed to obtain SDEs as a mathematical model of body sway on the basis of stabilograms.

We questioned whether the random force vanished from the mathematical model of the body sway. Using our Double-Wayland algorithm [26]–[27], we evaluated the degree of visible determinism in the dynamics of the COP sway. Representative results of the Double-Wayland algorithm are shown in Fig. 3. We calculated translation errors E_{trans} derived from the time series x (Fig. 3a, 3c). The translation errors E_{trans}' were also derived from their temporal differences (differenced time series). Regardless of whether a subject was exposed to the 3D movie on the HMD (III), the E_{trans}' was approximately 1.

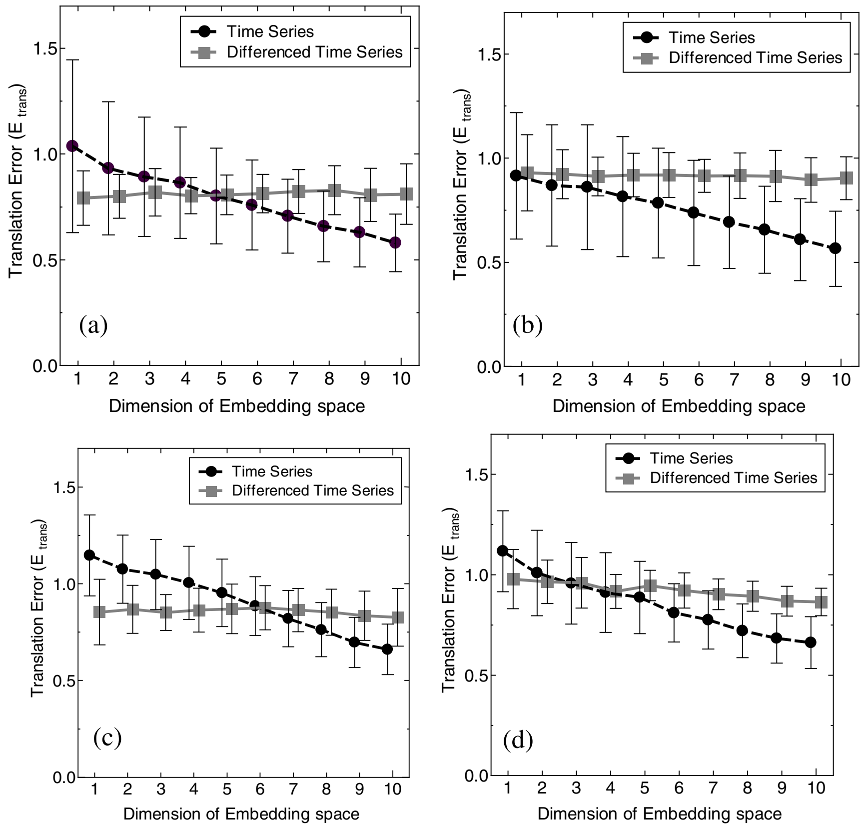

Fig. 3. Mean translation error for each embedding space. The translation errors were estimated from the stabilograms that were observed when subjects viewed a static circle (a)–(b) and conventional 3D movie on the HMD (c)–(d). We derived the values from the time series y (b), (d).

The translation errors in each embedding space were not significantly different from those derived from time series x and y. Thus, $E_{\mathrm{trans}} > 0.5$ was obtained using the Wayland algorithm, which implies that the time series could be generated by a stochastic process in accordance with a previous standard [28]. This 0.5 threshold is half of the translation error resulting from a random walk. Body sway has previously been described by stochastic processes [4]–[7], which were shown using the Double-Wayland algorithm [29]. Moreover, $0.8 < E_{\mathrm{trans}}' < 1$ exceeded the translation errors E_{trans} estimated by the Wayland algorithm, as shown in Fig. 3b. However, the translation errors estimated by the Wayland algorithm were similar to those obtained from the temporal differences, except for the case in Fig. 3b, which agrees with the abovementioned explanation of the dynamics for controlling a standing posture. The exposure to 3D movies would not change the dynamics into a deterministic one. Mechanical variations were not observed in the locomotion of the COP. We 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 the conventional 3D movie on the HMD. The indices for the stabilograms might reflect the coefficients in stochastic processes, although no significant difference in translation error was seen in a comparison of the stabilograms measured during exposure to (I) and (III). Regarding the system to control our standing posture during exposure to the 3D movie on the LCD (II), similar results were obtained.

The anterior-posterior direction *y* was considered to be independent of the medial-lateral direction *x* [30]. SDEs on the Euclid space $\mathbf{E}^2 \ni (x, y)$

$$\frac{\partial x}{\partial t} = -\frac{\partial}{\partial x} U_x(x) + w_x(t) \tag{2}$$

$$\frac{\partial y}{\partial t} = -\frac{\partial}{\partial y} U_y(y) + w_y(t) \tag{3}$$

have been proposed as mathematical models for generating stabilograms [4]–[7]. Pseudorandom numbers were generated by the white noise terms $w_x(t)$ and $w_y(t)$. Constructing nonlinear SDEs from the stabilograms (Fig. 1) in accordance with Eq. (1) revealed that their temporally averaged potential functions, U_x and U_y, have plural minimal points, and fluctuations can be observed in the neighborhood of these points [7]. 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.

Regardless of the display on which the 3D movies were presented, multiple comparisons indicated that the total locus length during exposure to the stereoscopic movies was significantly larger than that during the resting state (Fig. 2b). As shown in Fig. 1b and 1c, obvious changes in the form and coefficients of the potential function (1) occur. Structural changes might occur in the time-averaged potential function (1) with exposure to stereoscopic images, which are assumed to reflect the sway in the center of gravity. We considered that the decrease in the gradient of the potential increased the total locus length of the stabilograms during exposure to the stereoscopic movies. The standing posture becomes unstable because of the effects of the stereoscopic movies.

Most of the indices during exposure to the 3D movie on the HMD were significantly greater than those in the resting state, although there was no significant difference between the indices of the stabilograms during the resting state and those during exposure to the 3D movie on the LCD (Fig. 2). In this study, the apparent size of the LCD was greater than that of the HMD. Despite the size and visual distance, the 3D movie on the HMD affected the subject’s equilibrium function. Hence, by using the indicators involved in the stabilograms, we noted postural instability during exposure to the conventional stereoscopic images on the HMD. The next step will involve an investigation with the goal of proposing guidelines for the safe viewing of 3D movies on HMDs.

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