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Evaluation of High-quality LCDs Displaying Moving Pictures by Use of the Form Obtained from Statokinesigrams and the Dynamics

Kazuhiro FUJIKAKE[1]*, Hiroki TAKADA[2], Masako OMORI[3] and Masaru MIYAO[1,4]

[1]*Graduate School of Information Science, Nagoya University, Chikusa-ku, Nagoya 464-8601, Japan*
[2]*Gifu University of Medical Science, 795-1 Nagamine, Ichihiraga, Seki 501-3892, Japan*
[3]*Faculty of Home Economics, Kobe Women's University, 2-1 Aoyama Higashisuma, Suma-ku, Kobe 654-8585, Japan*
[4]*Information Technology Centre, Nagoya University, Chikusa-ku, Nagoya 464-8601, Japan*
**E-mail address: fujikake@nagoya-u.jp*

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Abstract. Optically compensated bend (OCB) mode liquid crystal display (LCD) panels are newly developed displays that have an excellent moving picture quality that is almost equivalent to that of a cathode-ray tube display. By measuring the centre of gravity of the human body, we compared statokinesigrams (SKGs) obtained from subjects viewing moving maps on the OCBs and on conventional model displays. Indices for the form of SKGs are useful for evaluating the LCD displaying the movie. We conclude that our method, where a subject views an LCD displaying a scrolling movie, is effective in evaluating the characteristics of movies being displayed on LCDs.

1. Introduction

Nowadays, liquid crystal displays (LCDs) are extensively used as general visual display terminals. They have several features such as large display size, reduction in weight and size because of miniaturization, and low power consumption. However, users viewing movies on LCDs often complain of the blurring and bleeding of images.

Many researches have been conducted previously for obtaining legible character displays on the screen. The optimal brightness ratios required for displaying characters as well as the background were obtained from ergonomic experiments (KIMURA *et al.*, 1990; SCHARFF and AHUMADA, 2002). SCHARFF *et al.* (2000) also examined the legibility of the colors in the characters. In comparison with backlit LCDs, it has been observed that non-backlit LCDs reduce the focusing speed among young subjects and the reading performance among middle-aged subjects (MIYAO *et al.*, 1993). With regard to the readability of sufficiently large characters, no significant difference was observed between the high- and standard-resolution video display terminals (VDTs). However, for very small characters, a higher resolution was found to improve the readability (MIYAO *et al.*, 1989). OMORI *et al.* (2002) and HASEGAWA *et al.* (2005) stochastically discussed the aspect ratio involved in the readability of characters on the LCDs of mobile phones. On the other hand, optokinetic stimulation (OKS) is known to trigger motion sickness (LESTIENNE *et al.*, 1977). Anterior displacement of the centre of gravity was observed during the body sway. In particular, the displacement increased when random dots were rotated vertically at a speed of 40–60 deg/s as an OKS to the subjects. However, there has been no study to evaluate the LCDs viewed by subjects using the data obtained from statokinesigrams (SKGs). By the way, the centre of gravity could be measured in accordance with stabilometry in which many of the earlier studies limited the analysis of the plots to summary statistics, i.e., calculation of the length of sway path, average radial area, etc. (DIENER *et al.*, 1984; KIRBY *et al.*, 1987; NORRĒ *et al.*, 1987; HASAN *et al.*, 1990). By doing so, these investigations ignored the dynamic characteristics of stabilograms.

When users viewed moving pictures on LCDs, they experienced a visually induced motion sickness that was caused by a disagreement between the visual stimulation and the stimulation of the inner ear (REASON, 1978). The blurred images on the LCDs sometimes induced "image sickness" in viewers, which is an unpleasant feeling that is similar to motion sickness. Significant increases in the postural sway were observed during the image sickness induced by simulator (STOFFREGEN and SMART, 1998).

Typical LCDs are said to be inferior to cathode-ray tube (CRT) displays with regard to motion picture display. This is because while a CRT is an impulse-based display and the temporal waveform of each pixel is a luminance impulse that is only a few milliseconds long, a typical LCD is a voltage-hold-type display, which implies that the voltages across the pixels are held during the entire frame period (16.7 ms). A voltage-hold-type display has a blur in its motion-frame picture because while human eyes track the movement of the picture, the picture is fixed for a certain period (field period) and a time gap is generated in its display. These problems can be avoided in LCD displays by using the pseudo-impulse driving method to realize a higher performance. In newly developed optically compensated bend (OCB) displays, the pseudo-impulse driving method is used to insert a black period between two continuous frames. The longer the black display period is, the closer it is to impulse-type displays. In the subjective evaluation of a blur, picture quality of such displays is fairly close to that of a CRT at and above 25% of black-frame insertion and is equivalent at 50%. Since the response time of the OCB display used in our experiment is less than 5 ms, black frames can be correctly inserted. In conventional LCDs, the liquid response time is too short for inputting a black signal. Pseudo-impulse driving technology can be applied only to high-speed OCB displays. A black-frame inserted band scans vertically on an OCB screen at a frequency of 60 Hz.

In this study, a newly developed LCD was compared with a previous model. By using a stabilometer, we compared the sway of the centre of gravity for the two abovementioned displays. The centres of gravity when the subjects were viewing moving maps were compared.

2. Method

We adjusted the temperature in the experiment room, which was kept dark, to 25°C. The photograph shows the experimental setting.

The subjects stood without moving on the detection stand of a stabilometer (G5500,

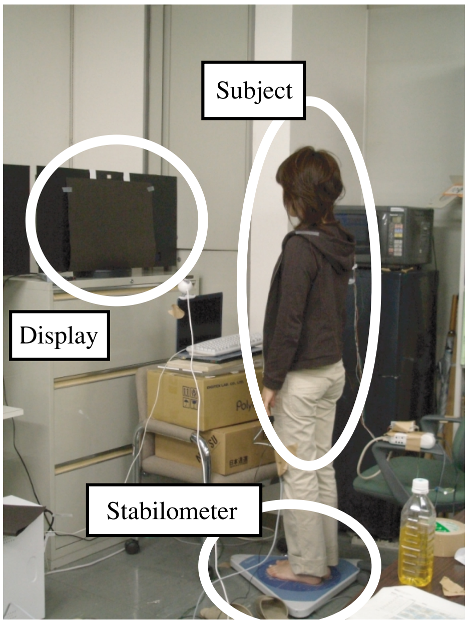

Fig. 1. Experiment setup.

Anima Co., Ltd.) in the Romberg posture with their feet together for 1 min before the sway was recorded. A centre of pressure (COP) was measured as a projection of the centre of gravity on to a force plate. Each sway of the COP was then recorded with a sampling frequency of 20 Hz.

The subjects first stood with their eyes open for 1 min (resting state); they then viewed a moving map on each display for the next 1 min (testing state). Subsequently, they closed their eyes for 1 min in order to evaluate effect of moving map task on the body of sway after the visual stimulus. The viewing distance was 1 m (Fig. 1).

Display device

We used two types of displays—the display of a previous LCD model and an OCB display. The former was a hold-type display of a typical LCD model, while the OCB display was of the newly developed pseudo-impulse-drive type.

The OCB display used in our experiment is a 32-inch LCD with a contrast ratio of 600:1. Its response time is 4.5 ms. It is sufficiently quick compared to the field period of 16.7 ms and is over 6 times quicker than other LCDs. The basic principle of the OCB-mode LCD had been presented in 1993. The main difference between the conventional TN (twisted nematic) liquid crystals and OCB liquid crystals is the alignment of the liquid crystal molecules between the glass substrates; the alignments were converted from the splay state to the bend state. When a voltage is applied to the bend-aligned liquid crystal molecules, the bending degree changes and optical compensation is performed between the

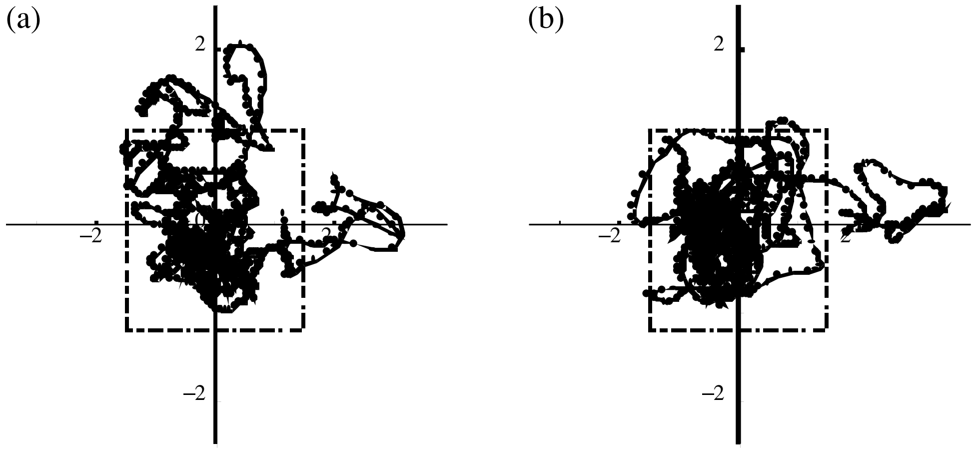

Fig. 2. Typical examples of SKGs extracted from a subject (a) viewing the display of a previous LCD model (previous model display) and (b) viewing the OCB display.

two polarizing plates arranged such that the liquid crystal cell is sandwiched between them; this generates black-and-white images. The transition of the bend-aligned liquid crystal molecules accelerates the changes in the alignment and consequently, the OCB display is capable of a higher-speed response.

Subjects

The test subjects were six persons from 20 to 27 years of age with no history of equilibrium function problems.

Moving map task

The map of a fictitious city was scrolled from left to right (or right to left). The subjects had to read the name of a place from the moving map as a moving map task. The scroll speed of the moving map was 20 dots/s. We made a subject sit on the chair for 10 minute at least after the moving task on one display.

Evaluation

We calculated several indices that are commonly used in the clinical field (SUZUKI *et al.*, 1996) for SKGs such as "area of sway," "total locus length," and "total locus length per unit area." In addition, new quantification indices termed as "sparse density (SPD)," "total locus length of chain 1," "total locus length of chain 2," (TAKADA *et al.*, 2003a) and "translation error E_{trans}" (WAYLAND *et al.*, 1993) were also estimated (Appendix). These except for the last one are called indices for the form of statokinesigrams (IFS) in this paper.

3. Results

Typical SKGs, which represent examples of the stabilometry results, are shown in Fig. 2. The left and right figures show the results when a subject viewed the display of a previous

Table 1. Results from stabilometry (mean ± standard deviation).

Index	Resting state	Previous model display	OCB display
Area of sway (cm^2)	2.3 ± 1.0	6.8 ± 3.4	4.9 ± 2.7
Total locus length (cm)	53.8 ± 16.4	96.5 ± 21.4	96.3 ± 22.0
Total locus length per unit area (1/cm)	38.8 ± 9.1	52.2 ± 10.4	56.3 ± 11.6
Sparse density S_2	1.3 ± 0.1	1.9 ± 0.2	1.7 ± 0.3
Sparse density S_3	2.0 ± 0.4	3.3 ± 0.4	2.7 ± 0.7
Total locus length of chain 1 (cm)	1.9 ± 1.4	3.3 ± 1.6	3.0 ± 1.5
Total locus length of chain 2 (cm)	1.7 ± 1.4	2.9 ± 1.5	2.4 ± 1.5

model and that of the OCB display, respectively. In these figures, the vertical axis shows the anterior and posterior movements of the centre of gravity, and the horizontal axis shows the right and left (lateral) movement of the centre of pressure. The squares (dashed line) in the two figures indicate the range recorded in the resting state (RS). The amplitudes of the sway as well as the lateral movement were larger when the subjects viewed the display of the previous model than when they were in the RS. There was no difference SKGs when there eyes were closed after the moving map task on the OCB display and previous one.

The measured values, except for the translation error E_{trans}, are shown in Table 1. In most cases, the values for the display of the previous model were higher than those for the OCB display. On the other hand, most E_{trans} values estimated by the Double-Wayland algorithm (Appendix) were larger than 0.5 for each embedding space (Fig. 3). There appeared to be no differences between the E_{trans} values derived from the time series data of the lateral and anterior/posterior directions. $0.8 \le E_{\mathrm{trans}} \le 1$ was obtained from the temporal differences of these time series (differenced time series).

4. Discussion

Information from the vision, vestibule, and somatosensory regions is managed at the centriciput in order to prevent falling down. The most widely known theory of motion sickness is based on the concept of sensory conflict (REASON, 1978; OMAN, 1982). STOFFREGEN *et al*. (1999) reported that the onset of motion sickness may be preceded by significant increases in postural sway. Instability in the standing posture can also occur due to anomalous eyesight, which exhibits some patterns in SKGs.

In order to evaluate display devices, a geostationary image and characters were generally used in previous studies (KIMURA *et al*., 1990; SCHARFF *et al*., 2000; SCHARFF and AHUMADA, 2002). We have proposed a new method for comparing the standing posture when a subject gazes at an LCD displaying a movie scrolling from the left to the right (FUJIKAKE *et al*., 2007). The moving pictures were rotated horizontally at a speed of 25 deg/s or less, which was considered to be a sufficiently small OKS. The speed was regarded as half of the maximum speed in order to follow smooth eye movements; therefore, the standing posture would be controlled by a mechanism regardless of whether or not the subjects viewed the moving pictures. This speculation was substantiated by the results in the translation errors.

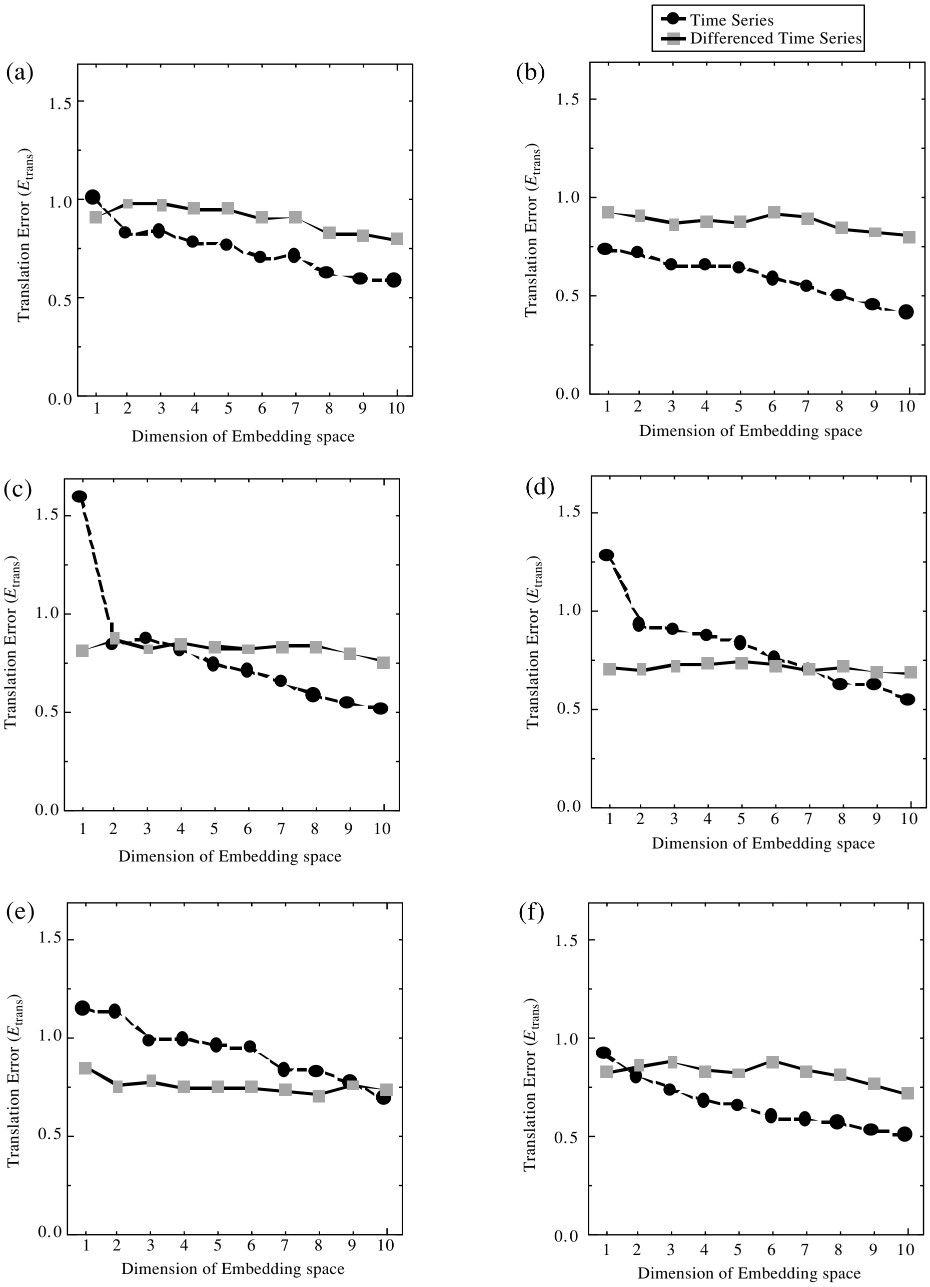

Fig. 3. For each embedding dimension, we calculated the translation errors that were derived from (a) lateral time series when subjects were in the RS, (b) anterior/posterior time series when subjects were in the RS, (c) lateral time series when subjects viewed the display of the previous model, (d) anterior/posterior time series when subjects viewed the display of the previous model, (e) lateral time series when subjects viewed the OCB display, and (f) anterior/posterior time series when subjects viewed the OCB display.

In this study, we mathematically measured the degree of determinism in the dynamics of the sway of COP. The Double-Wayland algorithm was used as a novel method. $E_{\mathrm{trans}} \geq 0.5$ was obtained by the Wayland algorithm, which implies that the 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 resulting from a random walk. The translation errors obtained from the subjects viewing the displays were similar to those of subjects in the RS (Fig. 3). Moreover, the body sway has been described previously by stochastic processes (COLLINS and DE LUCA, 1993; EMMERIK *et al.*, 1993; NEWELL *et al.*, 1997; TAKADA *et al.*, 2001), which was shown with the Double-Wayland algorithm (TAKADA *et al.*, 2005). $0.8 \leq E_{\mathrm{trans}} \leq 1$ obtained from the temporal differences of these time series exceeded the translation errors estimated by the Wayland algorithm, as shown in Figs. 3a and b. However, it was similar to the latter, except for the RS (Figs. 3c–f), which agrees with the explanation of the dynamics to control a standing posture. The moving map task would not change it into a deterministic one. Mechanical variations were not observed in the lateral locomotion of the COP. We assumed that the COP was controlled by a stationary process, and the sway in the RS could be compared with that when the subject viewed a display. The moving map task was thus regarded as an appropriate stimulus to evaluate the displays. IFS might reflect the coefficients in stochastic processes although the translation error did not exhibit a significant difference between the display of the previous model and the other one.

The anterior-posterior direction y was considered to be independent of the medial-lateral direction x (GOLDIE *et al.*, 1989). Stochastic differential equations (SDEs) on the Euclid space $\mathbf{E}^2 \ni (x, y)$

$$\frac{dx}{dt} = -\frac{\partial}{\partial x} U_x(x) + w_x(t)$$

$$\frac{dy}{dt} = -\frac{\partial}{\partial x} U_y(x) + w_y(t)$$

have been proposed as mathematical models that generate the SKGs (COLLINS and DE LUCA, 1993; EMMERIK *et al.*, 1993; NEWELL *et al.*, 1997; TAKADA *et al.*, 2001). Pseudorandom numbers were generated by the white noise terms $w_x(t)$ and $w_y(t)$. Due to the nonlinear SDEs constructed from the SKGs, their temporally averaged potential functions U_x, U_y have plural minimal points, and fluctuations could be observed in the neighborhood of the minimal points (TAKADA *et al.*, 2001). The variance in the SKG depends on the form of the potential function in the SDE; therefore, the SPD is regarded as an index for its measurement.

We statistically compared the RS among the testing states using the values of the indices that were used to evaluate the SKGs (Fig. 4). Among these states, the results of the one-way analysis of variance (ANOVA) exhibited a significant difference in all the indices except the total locus of chains ($p < 0.01$). From multiple comparisons, it was found that the values of indices other than the total locus length per unit area were significantly larger when the subjects viewed the display of the previous model than when they were in the RS

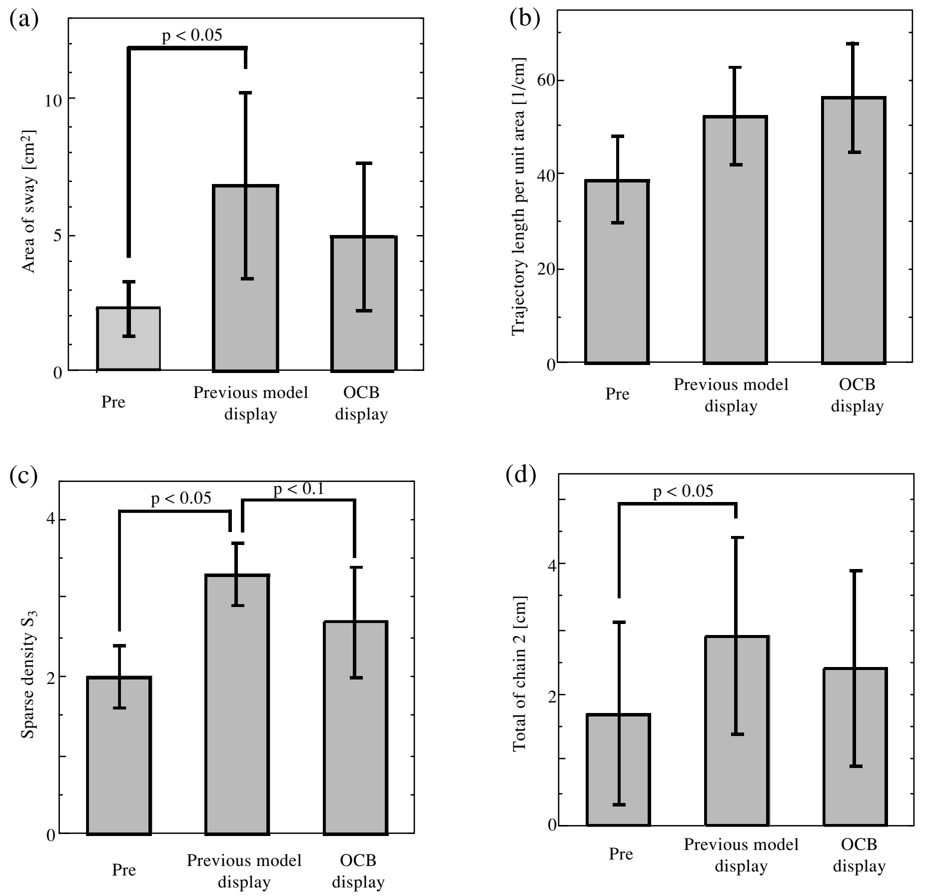

Fig. 4. We statistically compared the RS among the testing states using the values of the indices that evaluated the SKGs: (a) area of sway, (b) total locus length per unit area, (c) sparse density S_3, and (d) total locus length of chain 2.

($p < 0.05$). These statistical results indicated that visually induced motion sickness was affected by the display of the previous model. In contrast, there was no significant difference between the resting and testing states for the OCB display, although the values of the indices tended to be larger when the subjects viewed the OCB display than when they were in the RS. This result indicated that the use of the OCB display suppressed the visually induced motion sickness that was caused by the display of the previous model.

When the testing states for the display of the previous model were compared with the OCB display, no significant differences were observed in the indices other than SPD S_3 (see Appendix). This index S_3 may be convenient for evaluating the displays. According to previous researches, aging does not affect the SPD but it does affect the chains (TAKADA *et al.*, 2003b). However, the SPD of the stabilometry indicates whether the subjects had

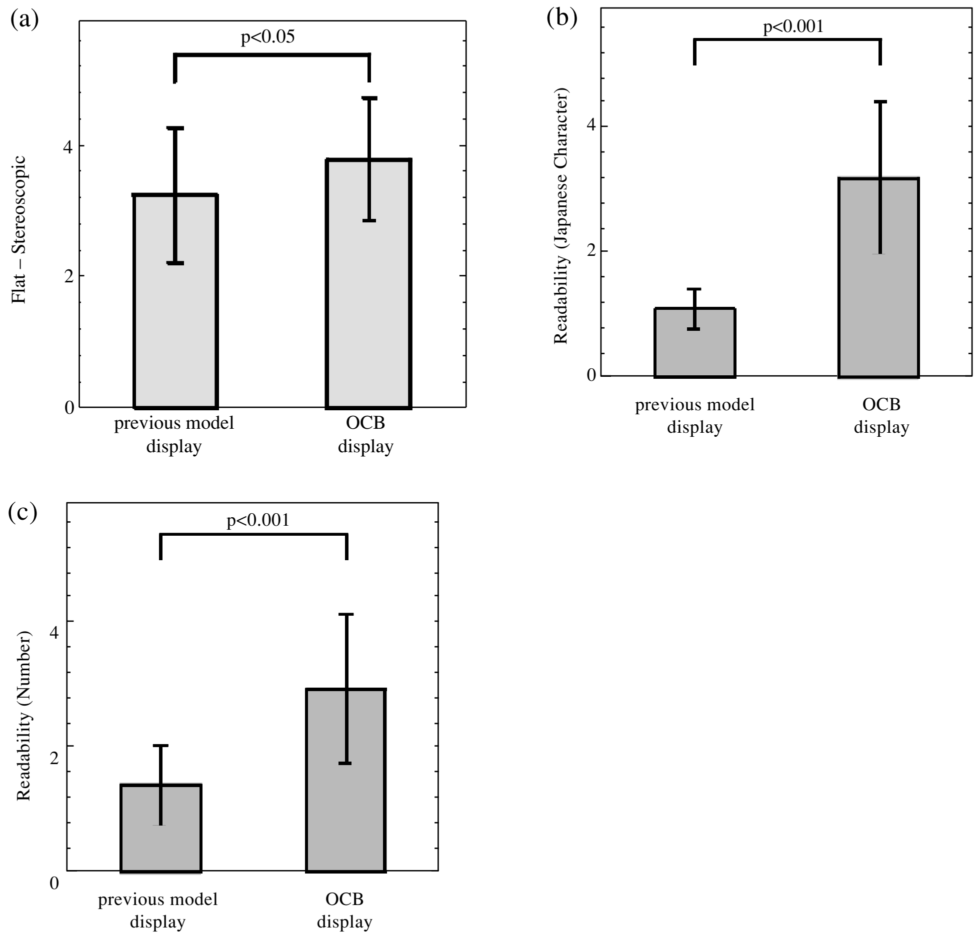

Fig. 5. Sensory evaluations for (a) depth feel, (b) readability (Japanese character), readability (number). A 5-point scale was used for the evaluation.

consumed alcohol an hour before the test (TAKADA *et al.*, 2003a). It is well known that the equilibrium function of the vestibule-cerebellum system deteriorates with the ingestion of alcohol as a medical reaction (KAGA, 1992). Therefore, the image sickness induced by the blurred images on LCDs might influence the vestibule-cerebellum system.

OCB displays have an excellent moving picture quality. The results of this study suggest that OCB displays are better than conventional displays for many applications. This result was consistent with subjective evaluations show in the Fig. 5 (MIURA *et al.*, 2005). We interviewed healthy adult with age 20–44 (21M, 17F), and the subject evaluated those display with the same protocol. 81.6% of them did not suffered from visually induced motion sickness during the moving map task on the OCB display.

5. Conclusion

In order to evaluate display devices, a geostationary image and the character were generally used in previous studies. We have proposed a new method for comparing the standing posture when a subject views an LCD displaying a movie scrolling from the left to the right. In this study, we mathematically measured the degree of determinism in the dynamics of the sway of COP. The Double-Wayland algorithm was used as a novel method. As a result, the dynamics of the sway when subjects viewed the movie as well that of the sway in the RS was considered to be stochastic. We assumed that the COP was controlled by a stationary process, and the sway in the RS could be compared with that when the subject viewed a display. The moving map task was thus regarded as an appropriate stimulus to evaluate the displays. IFS is useful for evaluating the LCD displaying the movie. We conclude that our method, where a subject views an LCD displaying a scrolling movie, was effective in evaluating the characteristics of movies being displayed on LCDs.

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Appendix

New quantification indices—"sparse density: S_2," "sparse density: S_3," "total locus length of chain 1," and "total locus length of chain 2"—were proposed by TAKADA *et al.* (2003a). Here, we describe SPDs, chains, and the translation error.

Sparse density (SPD)

SPD was defined by a scaling average of the ratio as $G_j(l)/G_j(k)$. An SKG was divided into quadrates whose latus is j times longer than the resolution, and $G_j(k)$ expresses the number of divisions including more than k measured points. If the centre of gravity does not move, the SPD value becomes 1. If there are variations in the SKGs, it becomes greater than 1. In this manner, SPD depends on the characteristic of the SKG and the motion process of the centre of gravity (TAKADA *et al.*, 2003a).

Chain

The force acting on the centre of gravity of the body was defined in terms of the difference in the displacement vectors. In particular, we focused on the singular points where statistically small or large forces were exerted. Based on these forces, the chains were eliminated from the SKG as a consecutive time series. If the times measured at these points were temporally vicinal, these points were connected by segments (sequences). The figures formed by these sequences are known as teamed chains because of the shape of the connections. "Chain 1" and "Chain 2" were defined by the figures of the sequences of the points where small and large forces were exerted, respectively; the former has local fluctuations or straight lines while the latter is a cusp pattern (TAKADA *et al.*, 2003a).

Translation error (Double-Wayland algorithm)

The translation error is a statistical index that measures the complexity of the dynamics generating the time series. In addition, the randomness can be evaluated by the Double-Wayland algorithm by comparing the transition errors in the temporal differences of the time series with the results of the Wayland algorithm in each embedding space.

Delay coordinates $\{\vec{x}_t\}$ can reconstruct a continuous trajectory without crossings in an embedding space that has a high dimension. Components of the delay coordinate cannot linearly correlate with each other if we only resample the time series at every delay time τ when the auto-correlation coefficient $\hat{\rho}(\tau)$ is regarded as zero. In this study, the auto-correlation function $\hat{\rho}(t)$ would be estimated from the time series data (MATSUMOTO *et al.*, 2002) and could be regarded as zero when $\hat{\rho}(t)$ decreases below 1/e for the first time ($t \geq 0$).

The Wayland algorithm assumes (WAYLAND *et al.*, 1993) that the difference vectors $\mathbf{v}_t = \vec{x}_{t+\tau} - \vec{x}_t$ in the embedding space are approximated to temporal variations of the trajectories and estimates the translation error in an m-dimensional embedding space (m = 1, 2, ..., 10).

(i) A series of delay coordinate vectors $\{\vec{x}_t\}$ is embedded in each space.
(ii) M onset periods t_0 are randomly selected.
(iii) The values of

$$E_{\text{trans}}(t_0) = \frac{1}{K+1}\sum_{i=0}^{K}\frac{|\mathbf{v}(t_i) - \bar{\mathbf{v}}|}{|\bar{\mathbf{v}}|} \tag{A1}$$

are standardized by the average of the difference vectors at $K + 1$ points $\{\vec{x}_{t_i}\}_{i=1}^{K}$.

$$\bar{\mathbf{v}} = \frac{1}{K+1}\sum_{i=0}^{K}\mathbf{v}(t_i) \tag{A2}$$

is obtained at every onset period, where the K points nearest to $\vec{x}_{t_0}$ are selected as $\{\vec{x}_{t_i}\}_{i=1}^{K}$.
(iv) The median of the M values of Eq. (A1) is extracted.
(v) Q medians are obtained by repeating the above steps. The translation error is estimated by the expectation value of these Q medians.
The Double-Wayland algorithm includes the following additional steps.
(vi) Translation errors are derived from the temporal differences of the time series by the Wayland algorithm outlined above.
(vii) If a DES that includes stochastic factors was the generator of the time series, the flow would not be smooth. In such a case, a significantly higher number of translation errors would be estimated in the last step than in step (v). Based on this result, we decide the stochasticity of the mathematical model that describes the time series data.

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