Effect of Unpredictable Motion Component in Video on Body Sway

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In this study, we verified the occurrence of visually induced self-motion during a motion movie that included both unpredictable and predictable components by measuring body sway. Eleven subjects watched a static movie for 1 min and 8 sinusoidally moving movies (direction setting: 2, added unpredictable component settings: 4) for 180 s each. The results revealed the following: First, a viewing depth-direction predictable motion movie had high phase synchronization acuity. In contrast, the unpredictable motion component considerably affected the viewing side-direction motion movie. Second, the relationship between the amount of added unpredictable motion components and the synchronization acuity was poor.

Key words: Vision, Body Sway, Reciprocator Motion, Unpredictable Motion, Predictable Motion

1. Introduction

The information derived from a visual system, vestibular-labyrinthine apparatus, and a somatosensory system is important for human posture control. To maintain posture, the integrated information in the brain is fed back to the whole body as information on self-position, direction, and posture. Edwards [1] reported that information from the visual system has the most significant effect on human posture control, constituting more than 50% of all input. Therefore, visual information is particularly important for posture control. An illusion phenomenon, called visually induced self-motion, is a prevalent phenomenon that indicates the importance of visual information. Visually induced self-motion is caused by an optic-flow input from the vision system. Such motion can be roughly divided into two types: visually induced self-motion in a direction opposite to the optic flow direction and that in the same direction. The former implies that visual information is only an applied sensation of self-motion. The latter implies that visual information is construed as the motion of the peripheral field. In other words, in the latter case, self-motion occurs according to the motion of the peripheral field (e.g., going with the river flow).

Previously, some studies on visually induced self-motion were conducted to analyze the relationship between movie characteristics and visually induced self-motion. For example, studies have investigated the occurrence of self-motion while viewing movies that contain changes in the velocity and acceleration [2,3] and the direction of movie motion. Other previous studies investigated the role of central vision and peripheral vision [4,5], and the role of the foreground and background in viewing movies that have two or more depth settings [6,7]. Moreover, and Britten [8] and Lappe *et al.* [9] reviewed the mechanisms or characteristics of visually induced self-motion.

Further, the occurrence of visually induced self-motion during reciprocator motion in the depth and horizontal directions during movie viewing has been investigated by measuring the body sway [10,11]. These studies have found that the position of the center of pressure (COP) moves in synchronization with the phase in the motion movie. Further, the higher the synchronization acuity in the direction of motion in the movie, the longer the viewing time. This study used a movie on the basis of a simple sinusoidal wave we could predict motion in the movie. Moreover, most previous studies on visually induced self-motion have used similar movies for estimating the predictable motion in the movie. However, we have had a greater opportunity to watch movies that contain unpredictable components using video-sharing websites on which amateurs upload their videos freely (YouTube™), camera-containing cellphones such as smartphones, and wearable devices such as Google Glass™. However, the occurrence of visually induced self-motion has not been investigated during the viewing of such movies. Therefore, the effect of an unpredictable motion component in the movie on visually induced self-motion is not clear. In this study, we verified the occurrence of visually induced self-motion during a motion movie containing both unpredictable and predictable components by measuring the body sway as a fundamental verification of the effect of an unpredictable motion component on the perception of visually induced self-motion.

2. Method

2.1 Movie creation and apparatus

A movie was created using the computer graphics software 3dsMax 2015 (Autodesk, USA). A screenshot of the movie used in this study is shown in Fig. 1. The basic construction of the movie shows a large number of balls at ran-

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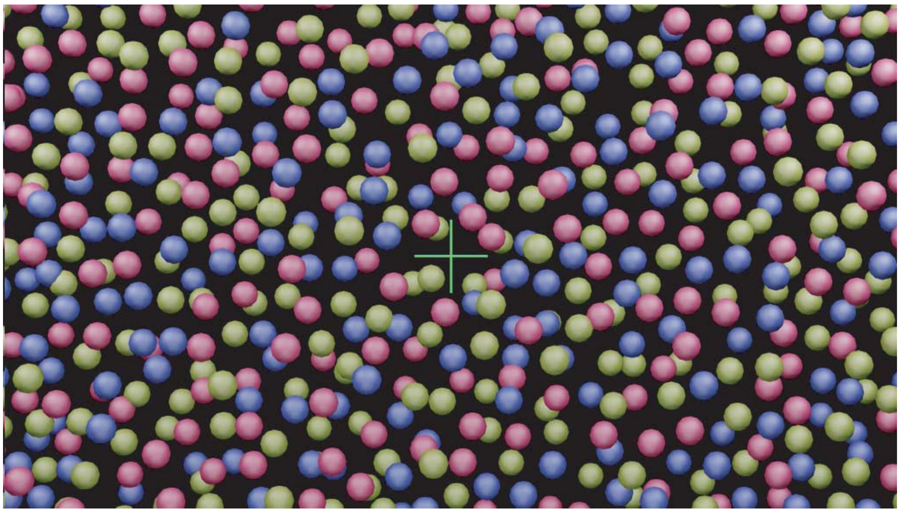


Fig. 1. Screenshot of the movie used in this study. A large number of balls at random positions and a green cross at the center position as the point-of-regard in the movie space. The direction of motion in the movie followed two patterns: depth direction (Z-direction) and side direction (X-direction), and the movies were 3-dimensional (3D) with binocular stereopsis.

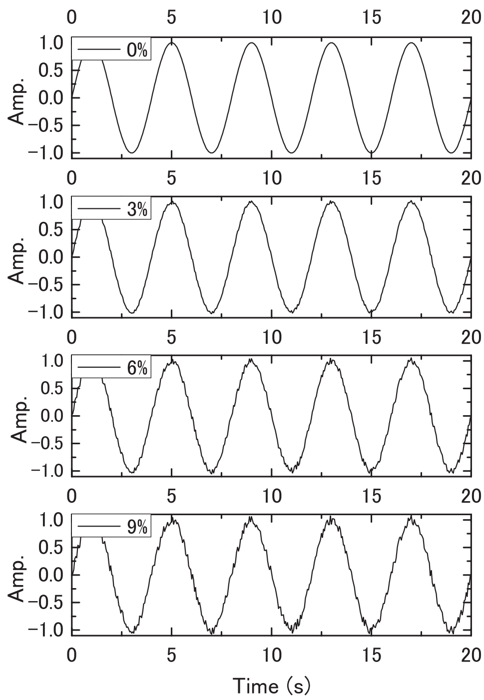


Fig. 2. Simulated motion added the unpredictable motion component in the movie. The amplitude of sine wave is standardized 1.

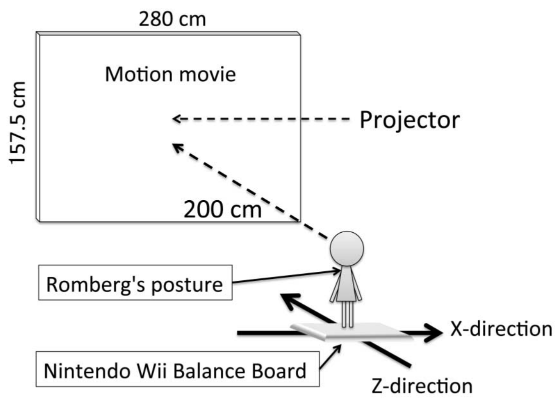


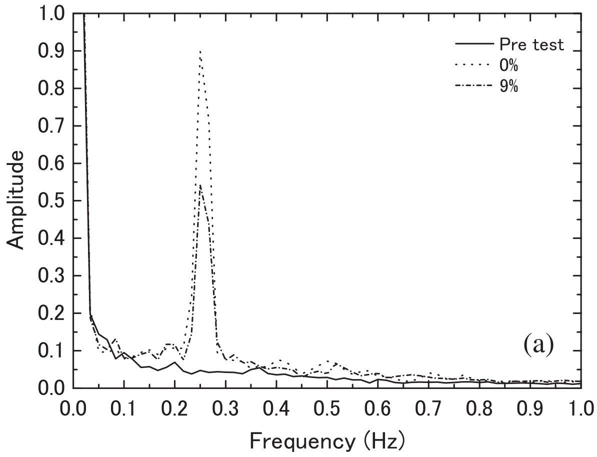
Fig. 3. The setup utilized in the study. The subject stood on a Wii Balance Board (Nintendo, Japan) in Romberg's posture. to measure body sway with a 2 m viewing distance to the screen.

dom positions and a green cross at the center position as the point-of-regard.

The direction of motion in the movie followed two patterns: depth direction (Z-direction) and side direction (X-direction). The motion in the movies was sinusoidal at 0.25 Hz in each direction and was generated by moving camera-simulated ocular globes (the balls did not move directly). The reason for adaptation of this frequency was that this study followed some previous study, which had reported that motion components under the 0.5 Hz provided large effect such as motion sickness on human [12,13,14]. The amplitude of the sinusoidal motion was set to 150 as a software setting in all directions. Moreover, we added the basic sinusoidal at 0.25 Hz to each uniform random number, which defined the maximum/minimum value as $\pm 3\%$, $\pm 6\%$, and $\pm 9\%$ of the amplitude of the sinusoidal motion for each direction of motion of the movie to create sinusoidal motion movies containing unpredictable components. The motion in the movie can be expressed as follows:

$$F(t) = A \sin(2\pi f t) + \epsilon, \tag{1}$$

where $F(t)$ denotes the position value at time t (s), A represents the amplitude of the sinusoidal, f indicates the frequency of the sinusoidal, and ϵ denotes the unpredictable component. Figure 2 shows simulated motion added the unpredictable motion component in the movie according to the above equation. For presentation, the movie was projected on a white wall 200 cm in front of a subject with a domestic version 2D/3D convertible projector (EH-TW5100, EPSON, Japan). The projected movie size was 157.5 cm (vertical) $\times$ 280 cm (horizontal), pixel size was 1,080 (vertical) $\times$ 1,920 (horizontal), and the viewing distance was 200 cm. Thus, the view angle was 38° (vertical) $\times$ 70° (horizontal).



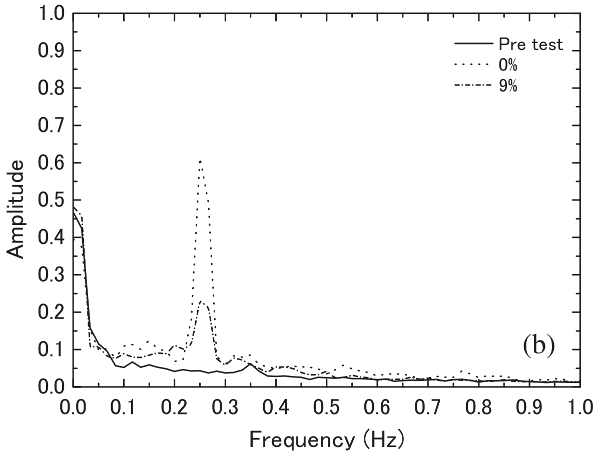


Fig. 4. An example of the frequency analysis result for body sway in the 11 subjects while viewing the static movie (pre-test) and the 0% and 9% movies (120–180 s). (a) shows result from viewing of the Z-direction motion movie, and (b) shows that of the X-direction motion movie.

The subject watched the experimental movies as 3D movies using 3D glasses (ELPGS03, EPSON, Japan) as a parallax barrier. To enable the measurement of the body sway during movie viewing, the subject stood on a Wii Balance Board (Nintendo, Japan) in Romberg's posture. In addition, to continuously obtain the position of COP, self-build stabilometry software termed FitTri ver.1.1c [15], along with WiimoteLib [16] for the Wii Balance Board made by Yoshimura, was used.

2.2 Procedure and design

Eleven students (5 male and 6 female, age range: 21–22 years) who did not have vision and equilibrium problems participated in this study. The study was approved by the Research Ethics Committee at Gifu University of Medical Science. Written consent was obtained from the participants after the purpose and significance of the study, and the nature and risk of the measurements were explained, both orally and in writing. Following this, the study was carried out in line with the Helsinki Declaration.

The setup utilized in the study is shown in Fig. 3. We performed measurements in a controlled environment (illuminance: 13 lx) to avoid variations caused by visual stimuli. The following protocol was adopted: First, a subject watched a static (non-moving) movie for 60 s as a pre-test. Next, the subject watched a sinusoidally moving movie for 180 s. By treating this 180-s task as one trial, eight trials (direction setting: Z-direction and X-direction, added unpredictable component settings: ±0% (normal sine wave), ±3%, ±6%, and ±9%) were performed in a random sequence to avoid the order effect. During the entire duration, the body sway was recorded continuously. The trial interval was set to more than 5 min.

2.3 Analysis

The measured position of the COP data is sampled at 100 Hz by the basic setting of the Wii balance board. However, a clinical test on the body sway using a stabilometer at 20 Hz is frequently performed. The COP data underwent downsampling at 20 Hz, following low-pass filtering at 10 Hz to adapt the clinical standard.

The continuous COP data were separated by intervals of 60 s of viewing time to analyze each time segment. Each separated data unit underwent a frequency analysis by a fast Fourier transform using the Hamming window. Moreover, the total locus length, which is one of the indexes for the instability of posture, was also calculated by each separated data unit.

3. Results

3.1 Example for temporally frequency analysis

An example of the frequency analysis result for body sway in the 11 subjects while viewing the static movie (pre-test) and the 0% and 9% movies (120–180 s) is shown in Figs. 4a (Z-direction) and 4b (X-direction), respectively. The graphs show the amplitude values (the square root of power) calculated from the Fourier analysis as the ordinate, and the frequency as the abscissa. For the static movie viewing, the amplitude value in the low-frequency band was relatively high. Moreover, a change in the amplitude value decreased with an increase in the frequency. Both graphs showed peaks at 0.25 Hz in only 0% and 9% movie viewing. However, the 0.25-Hz peak was missing for the static movie (pre-test). These results agree with the results of our previous studies [10,11]. Thus, the amplitude value at 0.25 Hz selectively increased while viewing only the motion movies. Considering that the peak frequency is 0.25 Hz, which is identical with the motion frequency of the movie, we may guess that an increase in the amplitude at this frequency implies that motion movies provide the body sway due to the self-motion illusion. Therefore, let us conduct an analyzing by focusing on the amplitude value of 0.25 Hz.

3.2 Extract measurement data

The various mental and physical effects of movie viewing on humans, such as visually induced motion sickness, are not uniform. In other words, the sensitivity effect caused by movie viewing depends on the person. The occurrence of visually induced self-motion is also no exception. The aim of this study is the verification of the effect of the unpredictable motion component through a verification of the occurrence of the visually induced self-motion during a motion movie containing both unpredictable and predictable components. To achieve this aim accurately, in this study, we should accept a particular analysis using removed subjects, who have extraordinarily low sensitivity to the mental

Table 1. Results of sorting subject data by using the Smirnov-Grubbs test with 5% significance level in the case of viewing a Z-direction motion movie.

	Amplitude at 0.25 Hz of body sway		
Subject No.	Open eyes without watching motion movie	Open eyes with watching motion movie from 0 to 60 s	Test for outliers
1	0.04401	1.82551	$P < 0.05$
2	0.08965	0.22626	$P < 0.05$
3	0.04744	0.1144	$P < 0.05$
4	0.06143	0.17953	$P < 0.05$
5	0.02724	0.20224	$P < 0.05$
6	0.0616	0.02785	n.s.
7	0.05878	0.31204	$P < 0.05$
8	0.04435	0.60125	$P < 0.05$
9	0.01222	0.12502	$P < 0.05$
10	0.03623	1.93987	$P < 0.05$
11	0.03819	0.34879	$P < 0.05$

Table 2. Results of sorting subject data by using the Smirnov-Grubbs test with 5% significance level in the case of viewing an X-direction motion movie.

	Amplitude at 0.25 Hz of body sway		
Subject No.	Open eyes without watching motion movie	Open eyes with watching motion movie from 0 to 60 s	Test for outliers
1	0.01	1.45761	$P < 0.05$
2	0.05663	0.45284	$P < 0.05$
3	0.02538	0.17415	$P < 0.05$
4	0.05311	0.1804	$P < 0.05$
5	0.03954	0.04632	n.s.
6	0.08922	0.03598	n.s.
7	0.04815	0.12394	$P < 0.05$
8	0.04233	0.81462	$P < 0.05$
9	0.02536	0.19244	$P < 0.05$
10	0.04323	0.44733	$P < 0.05$
11	0.04383	0.08547	n.s.

and physical effects of movie viewing. This is attributed to the fact that the inclusion of data of poor response subjects leads to an erroneous conclusion because they cannot be potentially affected by movie viewing. Thus, we use the following five-step method to sort out subject data in each direction:

I) Construct two sample-populations (one each in the Z- and the X-directions) using each individual amplitude value at 0.25 Hz in the case of static movie viewing. The number of samples is 11.

II) Add the amplitude value at 0.25 Hz in the time section from 0 to 60 s in the case of 0% movie viewing to the constructed sample population. The number of samples is 12.

III) Evaluate whether this sample population includes an outlier by using the Smirnov-Grubbs test with a 5% significance level. Here, the null hypothesis is that all data are attributed to the sample population.

IV) If the result of this test is insignificant, additional data are extracted in the target of the analysis.

V) Repeat Steps II) to IV) until the number of repetitions equals the number of subjects.

Tables 1 and 2 show the sort results obtained by following the above process. During Z-direction motion movie viewing, the data of subject No. 6 were extracted from the analysis target, and during the viewing of the X-direction motion movie, the data of subject Nos. 5, 6, and 11 were extracted.

3.3 Amplitude at 0.25 Hz in temporal frequency analysis

The temporal change in the amplitude value at 0.25 Hz in the frequency analysis while the variety of movie viewing was analyzed (Figs. 5a and 5b). Figure 5a shows the result obtained by viewing the Z-direction motion movies, and Fig. 5b shows that of the X-direction. The graphs show the amplitude values at 0.25 Hz calculated using the frequency analysis as the ordinate, and the time segments and type of movies as the abscissa. Error bars represent the standard deviation. 0% movie viewing in both directions increases the amplitude value with an increase in the viewing time. However, during viewing of the unpredictable component added to the motion movie, we did not confirm same tendency. The amplitude value at 0.25 Hz in the case of the 3% movie viewing was high in all time segments, as compared to the results of the 6% and 9% movie viewing. However, this

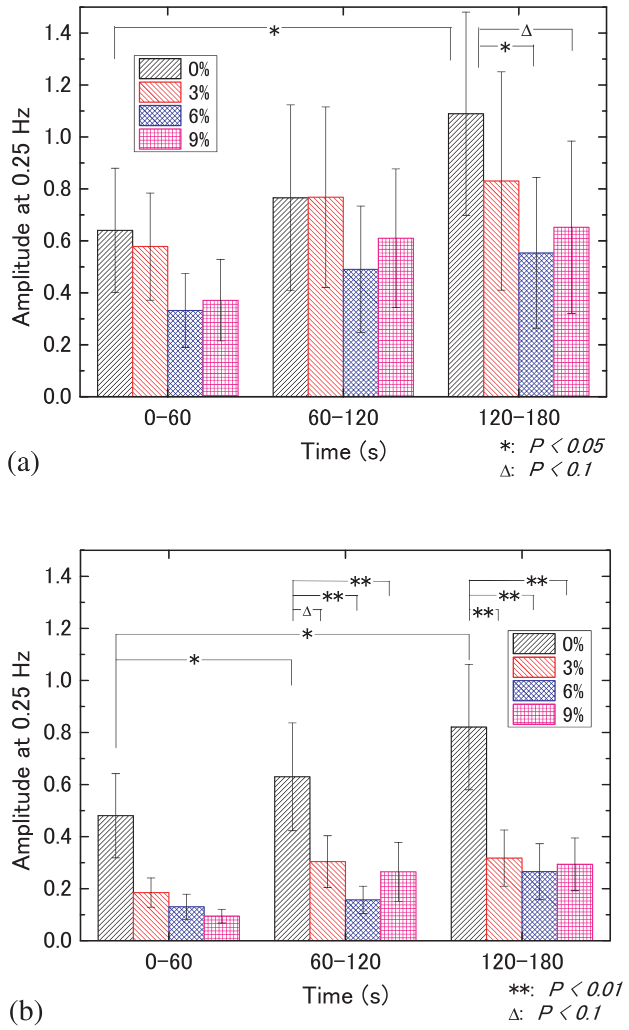


Fig. 5. The temporal change in the amplitude value at 0.25 Hz in the frequency analysis. (a) shows result from viewing of the Z-direction motion movie, and (b) shows that of the X-direction motion movie.

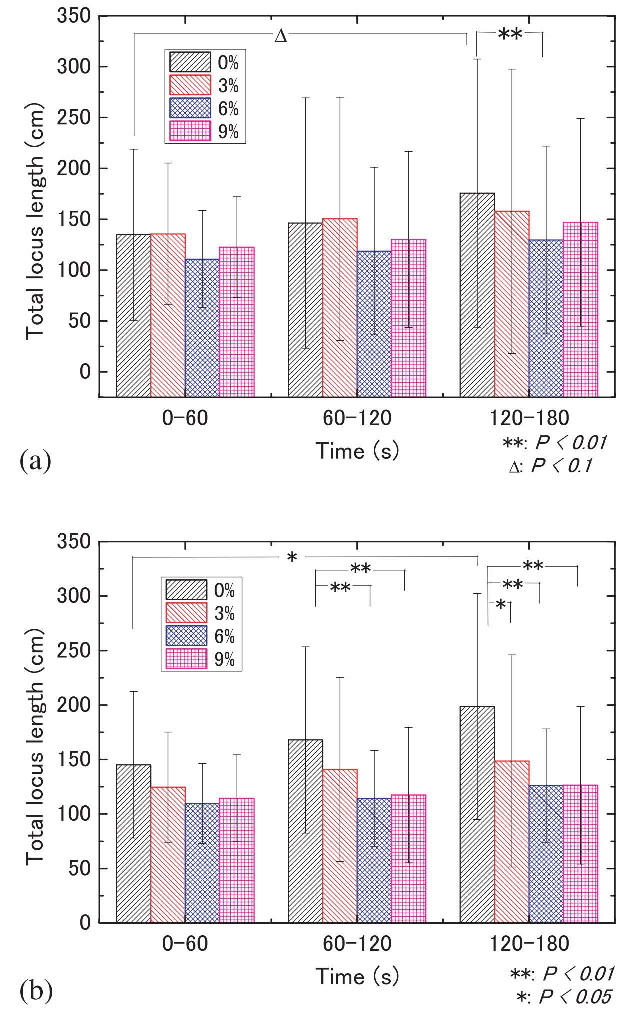


Fig. 6. The temporal change in the total locus length. (a) shows result from viewing of the Z-direction motion movie, and (b) shows that of the X-direction motion movie.

relationship showed no significant differences. In addition, we did not find an increase/decrease tendency matching the change in the amount of the unpredictable component. The difference between the amplitude values in the case of viewing a movie containing an unpredictable component (3% to 9% movie) and that in the case of viewing 0% movie in the X-direction were larger than that in the Z-direction. These temporal increases in difference changes indicated that the amplitude value at 0.25 Hz in the case of viewing a movie containing the unpredictable component changed little despite the increase in the amplitude value in the case of 0% movie viewing. When we used the Tukey-Kramer method with 3 time segments and 4 different amounts of the unpredictable components, significant differences were found, as shown in Figs. 5a and 5b.

3.4 Change in total locus length

The temporal change in the total locus length while viewing a variety of movies was analyzed (Figs. 6a and 6b). Figure 6a shows the results obtained in the case of viewing Z-direction motion movies, and Fig. 6b shows those obtained in case of viewing X-direction motion movies, as shown in Fig. 5. Both the result of the total locus length and the result of the frequency analysis at 0.25 Hz exhibited the similar tendency. First, while viewing the 0% movie of both directions, we found an increase tendency of the total locus length with an increase in the viewing time. For the difference in the amount of the unpredictable component, the total locus length while viewing the 3% movie was high in all time segments compared with the results for the 6% and 9% movie viewing. However, this relationship showed no significant differences. In addition, we did not detect an increasing/decreasing tendency according to the change in the amount of the unpredictable motion component. The difference between the total locus length observed while viewing a movie containing the unpredictable component (3% to 9% movie) and that in the case of viewing a 0% movie in the X-direction was higher than that in the Z-direction. This temporal increase change indicated that the total locus length in the case of viewing a movie containing the unpredictable component changes little in spite of the increase in the total locus length in the case of 0% movie viewing. When we used the Tukey-Kramer method with 3 time segments and 4 different amounts of the unpredictable component, significant differences were found, as shown in Figs. 6a and 6b.

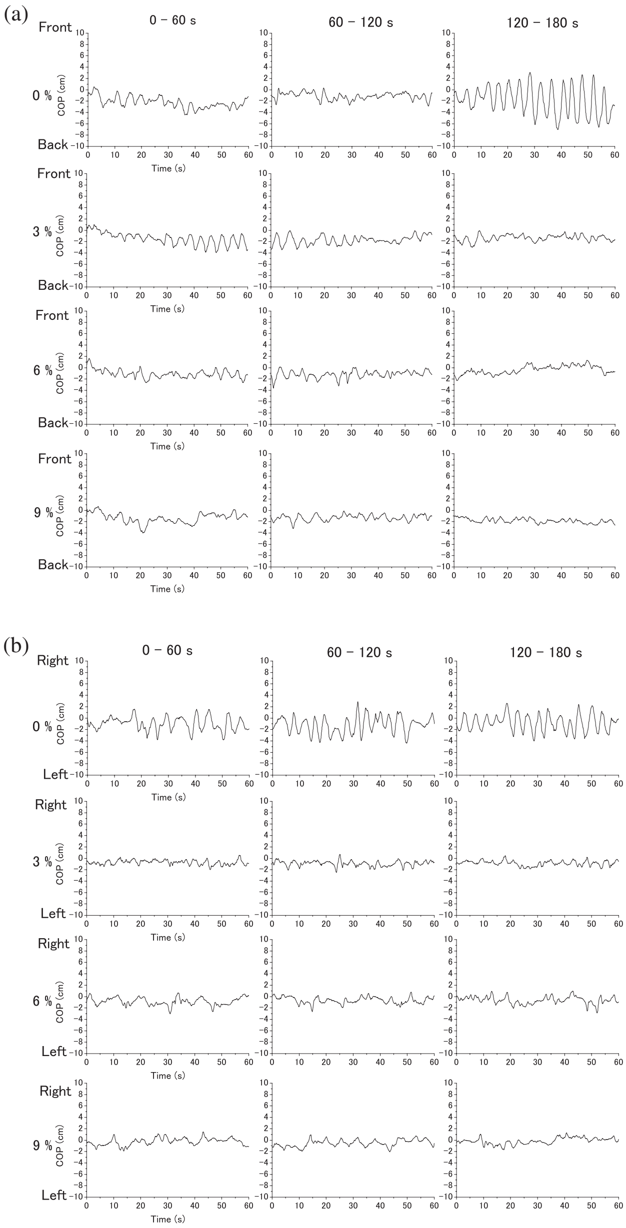


Fig. 7. Typical example for temporal change in COP (21 years old, female). (a) shows result from viewing of the Z-direction motion movie, and (b) shows that of the X-direction motion movie.

4. General Discussion

In this study, we quantified the perception of visually induced self-motion by measuring the body sway. This is based on some reports, such as Kuno *et al.* [17], Delome *et al.* [18], and Guerraz *et al.* [19], that state that the visually induced self-motion perception and the visually evoked postural responses have a high correlation. Both the result of the frequency analysis (Fig. 5) and that of the total locus length (Fig. 6) exhibited a similar tendency. This tendency can be explained by using Fig. 4, which shows the frequency analysis in the cases of static, 0%, and 9% movie viewing. The area of the graphs was, in the order of descending prevalence, 0%, 9%, and static movie viewing, because of peak creation at 0.25 Hz without the motion direction in the movie. The increased area may be interpreted as an increment in the kinetic energy of the body sway because the area of the graph was determined using the square root of power values. On the other hand, the total locus length, which is the sum of the moving distance of COP, represents the increment of velocity. The kinetic energy is proportional to the square of the velocity. Thus, both results are related to the change in velocity. Thus, similar results were delivered.

In the case of 0% movie viewing, the increase in the amplitude at 0.25 Hz with an increase in the viewing time while viewing the Z-direction movie was significantly higher than that while viewing the X-direction movie. Thus, this tendency indicated that while viewing a Z-direction motion movie, it was easier to observe the visually induced self-motion than while viewing a X-direction motion movie. One of the reasons for the visually induced self-motion is attributed to spatial perception (spatial swing) that was led by our previous demonstration experiment [10,11]. On the other hand, by considering the mechanistic dimension, a change in the body sway caused by the visually induced self-motion was also associated with the kinetic characteristics of posture control. When a human is able to maintain posture control, the center of gravity line (i.e., position of COP) stays inside of the base of support [20,21]. In Romberg's posture, the falling margin in the anteroposterior direction is bigger than that in the side direction because the base of support is longer in the anteroposterior direction. Therefore, the body sway in the Z-direction is easy to change than that in the X-direction.

For the viewing of the movie containing an unpredictable motion component, the result of viewing the 3% movie was most similar to that of viewing the 0% movie irrespective of the direction. In addition, as stated earlier, a consecutive increase/decrease tendency matching the amount of the unpredictable component was not found (Figs. 5 and 6). For the temporal change in the amplitude value at 0.25 Hz, the result of viewing the 3%, 6%, and 9% movie in the Z-direction indicated a gradual increase tendency without any significant changes, compared with that of viewing the 0% movie. In contrast, the result of viewing the 3%, 6%, and 9% movie in the X-direction did not exhibit a temporal change tendency, which is different from the result of 0% movie viewing. Moreover, significant differences were not found between 3%, 6%, and 9% movie viewing in each time segment. These results lead to the following two conclusions: The first is that viewing a Z-direction motion movie had high synchronization acuity to the phase in the motion component (low effect of the unpredictable motion component), compared with viewing the X-direction motion movie. The second is that the relationship between the amount of added unpredictable motion component and synchronization acuity is poor within the scope of this study. Let us discuss the reasons for these characteristics using Fig. 7. Figure 7 shows an example of the actual temporal change in the COP in the case of viewing a movie containing an unpredictable motion component. Figure 7a shows the condition of viewing the Z-direction motion movies, and Fig. 7b shows the condition of viewing the X-direction motion movies.

First, as stated before, our previous study [11] also reported that viewing a Z-direction motion movie had high phase synchronization acuity, compared with viewing an X-direction motion movie. Furthermore, our previous study indicated that the visually induced self-motion had an involvement in spatial perception [10]. With respect to the effect of the unpredictable motion component, we presumed that viewing a Z-direction motion movie containing an unpredictable motion component had a more considerable effect (easy to jumble the cyclic nature) on body sway than viewing an X-direction motion movie. However, the actual result was different. Therefore, it was considered that a comprehensive predictable motion component was associated with the spatial perception. In contrast, the imperceptible unpredictable motion component was only slightly associated with the spatial perception. Hence, we can attribute the possible association of the planar perception (non-spatial perception) to the positional relationship between the observation direction of the subject, motion direction in the movie, and direction of the unpredictable component. In the case of viewing an X-direction motion movie, the subjects recognize the unpredictable motion component as a relatively big movement. Thus, it is conceivable that the subjects were considerably affected by the unpredictable motion component through a sensation of planar perception. In contrast, in the case of viewing a Z-direction motion movie, the subjects recognize the unpredictable motion component as a relatively small movement because of the few planar transfers. Thus, we can conclude that the subjects were affected only slightly by the unpredictable motion component. This was confirmed by comparing Figs. 7a with 7b. The partial breakdown of the sinusoidal waves was extensively found in Fig. 7b, as compared to Fig. 7a.

Second, by assuming an increase in the amount of the unpredictable motion component as increasing the inhibitory factor, we believe that the amplitude value at 0.25 Hz decreased depending on the amount of the unpredictable motion component. However, from the actual result, we concluded that a significant change attributed to the difference in the amount of the unpredictable motion component was not found in each time segment. In addition, a temporal significant increase tendency in viewing a movie containing an unpredictable motion component was not found despite of finding such a tendency in the case of the 0% motion movie. Hence, it was, at least, a recognized effect of the unpredictable motion component within the scope of this study. However, a significant change in the effect of the difference in amount of containing an unpredictable motion component was not found. This was confirmed by both Figs. 7a and 7b, which clearly show the occurrence of a partial breakdown of the sinusoidal wave. Further, the interrupted cyclic motion of the body sway was not resumed immediately. By assuming the existence of the cyclic motion mode in terms of the sinusoidal waveform continuity shown in Fig. 7, we believe that the unpredictable motion component was a factor of the forced discontinuance of the cyclic motion mode or prevention of a restart of this mode. As discussed in more detail below, the unpredictable motion component worked as a trigger that stochastically disrupted the cyclic motion mode, and in the non-cyclic motion mode, it worked as a damper for the restart of the cyclic motion mode irrespective of the amount of the unpredictable motion component.

5. Conclusions

In this study, we verified the occurrence of visually induced self-motion while viewing a motion movie containing both unpredictable and predictable components by measuring the body sway as a fundamental verification of the effect of the unpredictable motion component on the perception of visually induced self-motion. The following were demonstrated:

I) Compared to viewing an X-direction predictable motion movie, viewing a Z-direction predictable motion movie had high phase synchronization acuity. In contrast, the unpredictable motion component considerably affected the viewing of the X-direction motion movie. This difference is attributed to the difference in perception of the predictive performance.

II) The relationship between the amount of the unpredictable motion component and synchronization acuity is poor within the scope of this study.

This study set the added unpredictable motion component to approximately 10% or less of the amplitude of the predictable sinusoidal at 0.25 Hz. Thus, in order to further understand this, we need to verify the occurrence of visually induced self-motion while viewing a movie containing additional 10% or more of the unpredictable motion component. Moreover, the occurrence of visually induced self-motion when there is a difference between the motion direction of the unpredictable motion component and that of the predictable motion component needs to be verified.

References

[1] Edwards, A. S. (1946) Body sway and vision, *J. Exp. Psychol.*, **36**, 526–535.

[2] Melcher, G. A. and Henn, V. (1981) The latency of circular vection during different accelerations of the optokinetic stimulus, *Percept. Psychophys.*, **30**, 552–556.

[3] Palmisano, S., Allison, R. S. and Pekin, F. (2008) Accelerating self-motion displays produce more compelling vection in depth, *Perception*, **37**, 22–33.

[4] Cheung, B. S., Howard, I. P. and Money, K. E. (1990) Visually-induced tilt during parabolic flights, *Exp. Brain Res.*, **81**, 391–397.

[5] Andersen, G. J. (1986) Perception of self-motion: psychophysical and computational approaches, *Psychol. Bull.*, **99**, 52–65.

[6] Brandt, T., Wist, E. R. and Dichgans, J. (1975) Foreground and background in dynamic spatial orientation, *Percept. Psychophys.*, **17**, 497–503.

[7] Ohmi, M. and Howard, I. P. (1988) Effect of stationary objects on illusory forward self-motion induced by a looming display, *Perception*, **17**, 5–11.

[8] Britten, K. H. (2008) Mechanisms of self-motion perception, *Annu. Rev. Neurosci.*, **31**, 389–410.

[9] Lappe, M., Bremmer, F. and van den Berg, A. V. (1999) Perception of self-motion from visual flow, *Trends Cogn. Sci.*, **3**, 329–336.

[10] Sugiura, A., Tanaka, K., Wakatabe, S., Matsumoto, C. and Miyao, M. (2015) Temporal analysis of body sway during reciprocator motion movie viewing, *Jpn. J. Hygiene* (accepted).

[11] Sugiura, A., Tanaka, K., Takada, H., Kojima, T., Yamakawa, T. and Miyao, M. (2015) A temporal analysis of body sway caused by self-motion during stereoscopic viewing, *Lecture Notes in Computer Science*, 8 LNCS_9176, 439–444.

[12] Griffin, M. J. and Mills, K. L. (2002) Effect of frequency and direction of horizontal oscillation on motion sickness, *Aviat. Space. Environ. Med.*, **73**, 537–543.

[13] Rosander, K. and Hofsten, C. V. (2000) Visual-vestibular interaction in early infancy, *Exp. Brain. Res.*, **133**, 321–333.

[14] Denise, P., Vouriot, A., Normand, H., Golding, J. F. and Gresty, M.

A. (2009) Effect of temporal relationship between respiration and body motion on motion sickness, *Auton. Neurosci.*, **151**, 142–146.

[15] A study group of rehabilitation tool, http://www.eonet.ne.jp/˜rpt/ (accessed December 25, 2014).

[16] Managed library for Nintendo's Wiimote, http://wiimotelib.codeplex.com/ (accessed December 25, 2014).

[17] Kuno, S., Kawakita, T., Kawakami, O., Miyake, Y. and Watanabe, S. (1999) Postural adjustment response to depth direction moving patterns produced by virtual reality graphics, *Jpn. J. Physiol.*, **49**, 417–424.

[18] Delorme, A. and Martin, C. (1986) Roles of retinal periphery and depth periphery in linear vection and visual control of standing in humans, *Can. J. Psychol.*, **40**, 176–187.

[19] Guerraz, M. and Bronstein, A. M. (2008) Mechanisms underlying visually induced body sway, *Neurosci. Lett.*, **443**, 12–16.

[20] King, M., Judge, J. and Wolfson, L. (1994) Functional base of support decreases with age, *J. Gerontol.*, **49**, M258–M263.

[21] Krebs, D. and Goldvasser, D. (2002) Is base of support greater in unsteady gait?, *Phys. Ther.*, 138–147.