Roles of Size, Position, and Speed of Stimulus in Vection with Stimuli Projected on a Ground Surface

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INTRODUCTION: Although the induction of vection (perception of illusory self-motion) has been studied for some decades, the effect of ground surface properties on vection remains to be assessed quantitatively. This study will be helpful for designing helicopter or airplane flight simulation, because pilots often perceive optic flow on the ground surface and perceive self-motion from such flows.

METHOD: Vection stimuli of variable position, size, and optic flow speed were presented in a trapezoidal area on a ground surface. Body sway was also measured.

RESULTS: Substantial vection was induced by stimuli on a ground surface. Increases in stimulus speed and size were each associated with stronger vection (e.g., the subjective strength increased by 50% as the speed increased from $0.375\ \text{m} \cdot \text{s}^{-1}$ to $1.5\ \text{m} \cdot \text{s}^{-1}$). When the stimulus occupied a more distant section of the visual field, vection was more efficiently induced than when the nearer section was occupied (e.g., the subjective strength decreased by 50% when the nearer half section of optical flow was removed). These properties of vection were similar to vection induced by upright vertical stimuli. Speed, size, and position of vection stimuli modified both length and direction of body sway significantly. Vection and body sway showed some correlations (e.g., $r = 0.55$).

CONCLUSION: Stimuli on ground surfaces can induce substantial vection and vection strength can be modified by the stimulus properties of the ground surfaces.

KEYWORDS: self-motion, body sway, optic flow properties.

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Mere exposure to a retinal optical flow induces a compelling illusion of self-motion called vection.[9] The first scientific experiment on vection was conducted by Brandt and colleagues.[4] Vection induction is facilitated when the visual stimuli (optic flow) occupy a large visual field. Research has consistently reported that a wider visual field induces stronger vection.[4,13,20] Additionally, a number of reports have indicated that the peripheral visual field is more effective than the central field for vection induction.[7,13,16] Brandt et al.[4] reported that stimuli presented to the central 30° of the visual field could not induce vection. However, stimuli presented in the peripheral 120° were able to induce strong vection. On the other hand, Post[30] reported that no part of the visual field was more effective than any other for vection induction. Nakamura[24] summarized extant studies and suggested that the differences in the efficiency of peripheral and central visual fields for vection induction reported in earlier studies can be explained by the perceived depth effect, e.g., stimuli in the peripheral visual field might be perceived as farther away than those in the central visual field.

Thus, from the earliest history of vection research, the relationship of the visual field to vection has received extensive attention. Almost all of these studies have projected vection stimuli on an upright vertical screen; however, in the real self-motion (locomotion) of our daily lives, we encounter ground surfaces. Gibson[11,12] suggested that the properties of the ground surface may be an important aspect of optic flow and hence for the perception of self-motion. Hence, ground surfaces are

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potentially important for flight, especially during takeoff and landing.

In the vision science of perceptual psychology, ground surfaces have been a subject of much recent attention. The term "ground dominance effect"[3] has been coined to describe some ground surface advantages in visual perception. For example, visual search tasks can be accomplished more efficiently on a ground surface versus a ceiling surface.[22] Additionally, accuracy of heading is enhanced more by optic flow on a ground surface than on a ceiling surface.[32] We can conclude here that our visual perception references the ground surface more frequently than the ceiling surface. Finally, Sato et al.[33] also reported that vection stimuli simulating the texture of a ground surface can induce stronger vection than can similar textures of ceiling or wall surfaces. These studies suggest that our visual perception references ground surfaces more frequently than ceiling surfaces.

As described above, a stimulus's position in the central versus peripheral visual field is an important factor for vection induction. Because ground surfaces are often perceived peripherally and also typically occupy a large proportion of the visual field, examining the role of these surfaces in vection is critically important. Yet few studies have addressed this topic. Flückiger and Baumberger[10] examined the effect of the ground surface on self-motion. They projected a texture composed of numerous uniformly-distributed spot-lights on a floor (4×14 m), and moved the texture at $1.4\ \mathrm{m \cdot s^{-1}}$ in a forward or backward direction as subjects viewed it. They monitored the postural responses of standing subjects when the optic flow was presented and, at the end of the experiment, asked subjects to describe the motion they had perceived. The postural measurement showed that an approaching texture caused a backward body inclination, and a receding texture caused a forward body inclination. Although all subjects reported the self-motion impression orally, the researchers did not collect any quantitative vection data, e.g., latency, duration, or subjective strength of the vection. The effectiveness of a ground surface on vection induction was assessed qualitatively; however, the quantitative measurement of this phenomenon remains a missing piece in vection research.

Baumberger, Isableu, and Flückiger[2] re-examined the effect of optic flow on a floor 16 yr later; however, they again emphasized postural response rather than devoting attention to other parameters of vection induced by a ground stimulus. Using adults and children between 7 and 11 yr of age as subjects, their study revealed that the characteristics of postural sway changed with advancing age. Unfortunately, their study's data were also limited to the recorded verbal responses of subjects' self-motion perception (vection) induced by the optic flow on the ground; quantitative assessment of vection latency, duration, and magnitude were not undertaken.

Recently, Trutoiu et al.[37] focused attention on the effect of the ground surface for vection induction; specifically, they examined the effects of the presence or absence of a ground surface in vection stimuli. They projected a 3D computer graphic of the city of Tübingen on a large and sophisticated hemispherical screen. Their results showed that adding the ground surface enhanced vection strength for linear vection, but not for circular vection. This result suggests that there is a facilitation effect on vection by the ground surface. However, it should be noted that their study was in the context of virtual reality and, therefore, they used meaningful stimuli. This was a critical issue because stimulus meaning can alter vection strength.[25,31,34] It is therefore still unclear what effects meaningless stimuli on the ground surface would have on vection induction. Furthermore, Trutoiu et al.[37] only examined the effect of the presence or absence of a ground surface. They did not qualitatively control the size and position of the stimuli on that surface.

The extant literature does not appear to include any vection studies in which the stimulus attributes of optic flow on the ground surface have been examined systematically, e.g., in the way that classical vection studies have examined factors like position and size in the visual field[7,13,16] and stimulus speed[8,23] as mediators of vection induction. Although it has been 26 yr since the first classical vection study was conducted, there has been no systematic development of knowledge about efficient and inefficient vection induction in optic flow on a ground surface. Such a systematic examination is one of the most important ways to move the field of vection research forward. Such work could benefit flight simulation given that ground surfaces seen in the display are likely to influence self-motion perception and subsequently the degree of immersion that takes place for the users.

The lack of studies focusing on ground surface vection can be attributed to the fact that, until recently, a huge apparatus was required for creating a ground-surface optic flow. Cost and environmental or logistical factors have likely been significant limitations in the past. Today, however, high-end projectors are available at a reasonable price. Therefore, if researchers are able to meet the space-related challenges of this experimental environment, studies that focus on ground-surface qualities will flourish.

In this study, we set some conditions on the size (position) and speed of optic flow on a ground surface that moved leftward. We obtained three vection measurements: latency, duration, and magnitude. These measurements have been implicated as the most important indices of vection.[36] We also obtained data on body sway, as Baumberger and colleagues did,[2,10] and we compared those data with vection indices and examined the relationship between vection and body sway of the subjects. With these design features in place, we felt confident that this study would fill in a gap in the field of vection research.

In the present study, the ground stimulus was created by the very simple procedure of placing the projector in an elevated location and inclining it toward the floor. Although this produced the defect that the stimulus was distorted into a diagonal shape, our setup allowed simulation of a very large visual field for the subject. We decided to ignore this stimulus distortion, as we felt the overall setup would still provide useful data on vection induction by the ground optic flow.

METHODS

Subjects

There were 12 adult volunteers (including the first author) who participated in the speed experiment [mean age: 43.3 ± 13.7 (SD); range: 26–58 yr; 3 men and 9 women], and 11 of the 12 individuals from the previous experiment participated. Subjects were employees of Paris Miki Inc. All subjects reported normal vision and no history of vestibular system diseases. All provided their written consent after being fully informed of the nature of the experiment, any hazards involved, and their right to withdraw from the experiment at any time without prejudice or penalty. No one except for the first author was aware of the purpose of the experiment.

Apparatus

The experiment was conducted in a dark chamber (18 × 18 × 9 m). Stimuli were generated and controlled by a computer (MacBookPro, MD101J/A; Apple, Cupertino, CA). The stimuli were projected on the ground by a liquid-crystal display projector (EH-TW600; Seiko Epson, Nagano, Japan). The refresh rate was 60 Hz and the resolution of the projector was 1280 × 800 pixels. The projector was placed 13 m from the subject at a height of 3.6 m with the projection angle fixed at 35° to the ground surface. The stimulus shape was a trapezoid (the upper base, lower base, and depth were 4, 8, and 7 m, respectively) (see **Fig. 1A**). We set the stimulus parameters to maximize the size of the optic flow.

For measuring body sway, we used a Wii balance board (Nintendo, Kyoto, Japan). It was placed in the middle of the bottom base of the trapezoid. It was connected to the computer by Bluetooth. The sampling rate of body sway was 60 Hz. Clark et al.[6] reported the high accuracy and validity of the Wii balance board for measuring body sway. Wei, Stevenson, and Kording[38] also used the device in their visual experiment. We used a Wii controller (Nintendo) for obtaining vection latency and duration. The sampling rate of the controller was also 60 Hz.

Stimulus

Optic flow displays [30° (trapezoid's top) × 136° (bottom) × 77° (depth) for the subject's eye level at 160 cm] consisted of 400 randomly positioned dots per frame with projected global dot motion that simulated rightward self-motion (leftward stimulus motion). Stimulus duration was 30 s. The subjective impression of the dots was a continuous leftward-moving optic flow display.

As described previously, the random-dot pattern was distorted in a trapezoidal shape. Each dot's shape was roughly circular, but its size changed as a function of position. The diameter of dots was about 3 cm beneath the subject's feet and 1.5 cm at the farthest distance. Similarly, the density of dots gradually increased toward the more distant end of the display.

There were five speed conditions for the dots: 0 (static dots), 0.375, 0.750, 1.125, and 1.500 $m \cdot s^{-1}$. Each of these five speed conditions was projected on the full stimulus field. These values reflect the speed of the dots at the subject's feet. The speed at the farthest distance from the subject was about half that at the subject's feet.

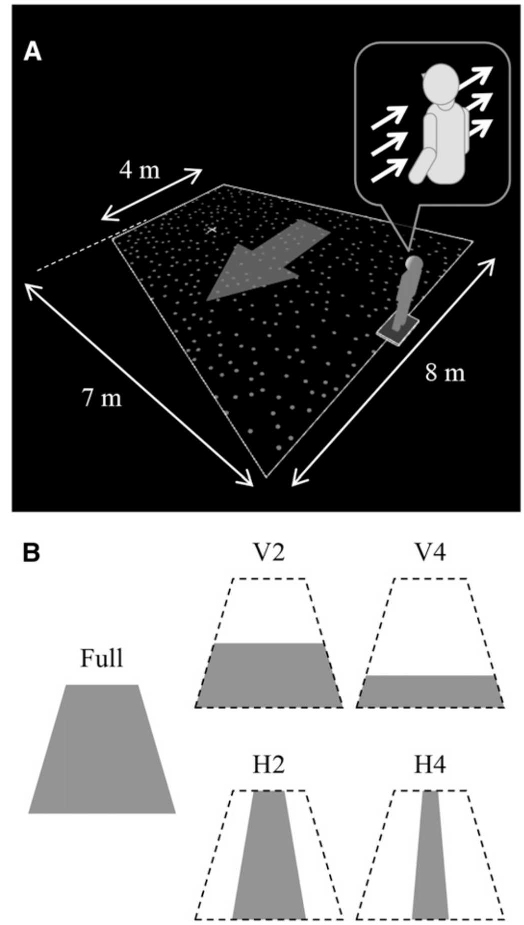

Fig. 1. A schematic illustration of A) the experimental environment and B) the five visual field conditions.

We also modified the size and position of the stimuli. There were five size-position conditions: full field, vertical half field (V2), vertical quarter field (V4), horizontal half field (H2), and horizontal quarter field (H4) (**Fig. 1B**). The positions and sizes of the stimulus fields were determined arbitrarily. We could not investigate all possible combinations of positions and sizes and, therefore, selected some practical conditions as a starting point. The speed of the dots in the five conditions was constant at 1.5 $m \cdot s^{-1}$. There was a fixation point throughout the experiment that was 5.4 m directly in front of the subject (Fig. 1A). The size of the fixation point was 16 cm × 16 cm (2° × 3° visual angle from a 160-cm distance).

Procedure

Subjects stood on the Wii balance board, which was placed on the middle point of the bottom base of the trapezoid. All subjects were in their stocking feet when they were on the balance board. They stood relaxing in Romberg's posture (following the suggestions by the Japan Society for Equilibrium Research[15]) with the Wii controller in the right hand. There are many previous studies in which Romberg's posture has been employed for measuring body sway.[17,19,27] They were instructed to look steadily at the fixation cross. The subjects first observed the standard stimulus, i.e., leftward full-field stimulus motion at constant velocity ($0.75\ m \cdot s^{-1}$) for 30 s. After that, a black screen with only the fixation point appeared for 5 s. The task of the subjects was to keep a particular button depressed whenever they were perceiving vection. Latency and duration of vection were measured. After the stimulus presentation period, the subjects rated subjective vection strength using an 11-point rating scale that ranged from 0 (no vection) to 10 (very strong vection). We instructed subjects to use the strength of vection that was perceived in the standard stimulus as "5" on that scale.

In the experiment that examined the speed of optic flow, the five speed conditions were randomly ordered and all five speed conditions were completed in one session. Each subject completed a single session over 3 d. All three sessions were completed within 1 or 2 wk. Each session lasted approximately 15 min, so no rest periods were given during sessions.

The experiment examining the size and the position of the stimulus visual field was conducted after all subjects had completed the speed experiment. There were two sessions, in each of which only vertically modulated (V2 and V4) or horizontally modulated (H2 and H4) conditions were conducted. In the session, these two conditions (V2 and V4, or H2 and H4) were randomly ordered. We repeated each session three times. In a single day, two sessions (vertically and horizontally modulated stimuli) were conducted. The order of conducting the two sessions was counterbalanced over the 11 subjects. Each session could be completed within 15 min, so there was no rest period offered.

Body sway measurements were obtained for all experimental trials. At the conclusion of the vection trials, we obtained a baseline (the control condition) body sway measure by having subjects simply focus on the fixation cross for 30 s with no other visual stimulus present. This condition was repeated three times to be consistent with procedures in the vection trials.

In studies by Flückiger and Baumberger,[2,10] the center of body gravity was captured just at the onset and offset of the visual stimulus presentation. In this study, we wanted to know the relationship between vection and body sway; therefore, we focused on the whole trace of the body sway measurement during the entire stimulus presentation period (30 s).

Data Analysis

In **Fig. 2**, we show an example of body sway data, representing all the traces of the center of foot pressure (CoP) for one subject in a single 30-s trial. This subject clearly experienced a greater sway in the lateral than in the anterior–posterior directions. To characterize each subject's body sway, we chose two parameters: distance (total length) and the vector (mean position vector in eight directions). These parameters have been recommended as indices of body sway by the Japan Society for Equilibrium Research.[15] Total length of body sway is defined as the sum of all CoP traces. Total length was calculated by

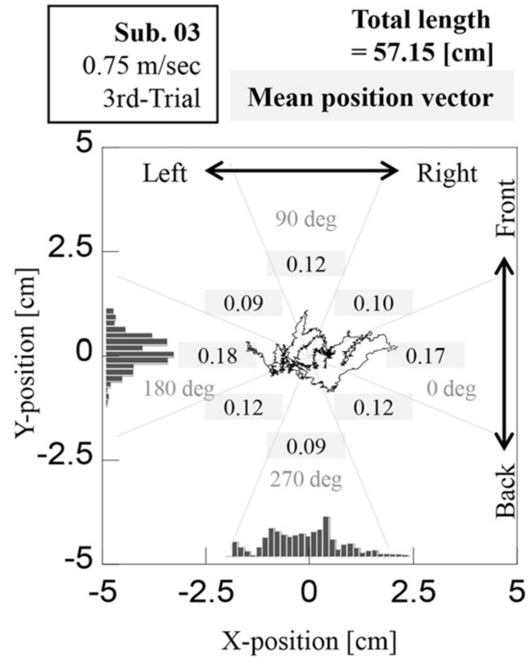

Fig. 2. Trajectory of body sway. Histograms show the probability density distributions of body sway on the x- or y-axis. The highlighted values show the mean position vectors in this trial.

$$Total\,length = \sum_{i=1}^{n=1} \sqrt{\left(X_{i+1} - X_i\right)^2 + \left(Y_{i+1} - Y_i\right)^2}$$

In this, X and Y denote horizontal (lateral) and vertical (antero–posterior) displacement of body sway, respectively.

The mean position vector is defined as the vectorial representation of body sway. To calculate the mean position vectors, we first divided the field of the possible area of body sway into eight areas (directions): right, right front, front, left front, left, left back, back, and right back. For convenience, we labeled these eight areas 0° to 315° in 45° increments (see Fig. 2). The sum of the distances between the mean center of gravity of the body and all sampling positions of the body on each area is given as follows:

$$L_k = \sum_{i=1}^{Nk} \sqrt{\left(X_i - \overline{X}\right)^2 + \left(Y_i - \overline{Y}\right)^2}$$

In this equation, $\overline{X}$ and $\overline{Y}$ denote the mean point of horizontal (lateral) and vertical (antero-posterior) body sway, respectively. Nk is the number of data points that fall into area 'k' (e.g., 0°).

Finally, mean position vectors were calculated by:

$$Mean\,Position\,Vector = \left(L_k / N_k\right) \div \sum_{k=1}^{8} \left(L_k / N_k\right)$$

In this, eight areal mean distances (Lk / Nk) were divided by the sum of them, respectively. Examples of the results of mean position vector of sway are presented in Fig. 2. The mean position vector of the left direction (180°) was 0.18, and that of the right (0°) was 0.17. In this subject, the horizontal (left-right) position vectors' sum was more than 35% of the total vector lengths. By comparing values in this way, we could understand the global picture and also the major tendencies of body sway.

Repeated measures one-way analysis of variance (ANOVA) were used to test differences of vection and body sway measurements in the five speed conditions and five visual field conditions. For all multiple comparison tests, Tukey's method was used. To examine the relationship between the parameters of vection and postural sway, we calculated the correlation coefficients and tested their validity using Student's *t*-distribution.

RESULTS

The results for the three vection measures in the five speed conditions are shown in **Fig. 3A**. Vection duration and intensity increased and vection latency decreased as optic flow speed increased. One-way ANOVAs for the three vection measures confirmed a significant main effect of speed on latency, duration, and magnitude [duration: $F(4,44) = 23.583, P < 0.001$; latency: $F(4,44) = 8.269, P < 0.001$; magnitude: $F(4,44) = 24.180, P < 0.0001$]. Multiple comparisons revealed significant differences in duration between the 0.000 $m \cdot s^{-1}$ condition and the other four conditions (0.375 $m \cdot s^{-1}$: $P = 0.0148$; 0.75 $m \cdot s^{-1}$: $P < 0.0001$; 1.125 $m \cdot s^{-1}$: $P < 0.0001$; 1.5 $m \cdot s^{-1}$: $P < 0.0001$). In latency, there were significant differences between the the 0.000 $m \cdot s^{-1}$ and the three higher three speed conditions (0.75 $m \cdot s^{-1}$: $P = 0.0074$; 1.125 $m \cdot s^{-1}$: $P = 0.0092$; 1.5 $m \cdot s^{-1}$: $P = 0.0015$). In magnitude, there were significant differences between the 0.000 $m \cdot s^{-1}$ condition and the three higher speed conditions (0.75 $m \cdot s^{-1}$: $P = 0.0003$; 1.125 $m \cdot s^{-1}$: $P < 0.0001$; 1.5 $m \cdot s^{-1}$: $P < 0.0001$), and between the 0.375 $m \cdot s^{-1}$ condition and the two higher speed conditions (1.125 $m \cdot s^{-1}$: $P = 0.0067$; 1.5 $m \cdot s^{-1}$: $P = 0.0013$).

Results of calculations of total length of body sway are shown in **Fig. 3B**'s left panel. It appears that the total length of body sway increased as dot speed increased. The one-way ANOVA confirmed this main effect of speed [$F(5,55) = 3.383, P = 0.0098$]. Multiple comparisons did not reveal any significant difference between any combinations of speed conditions.

In Fig. 3 B's right panel, we present the results of the mean position vectors. In the right (0°)

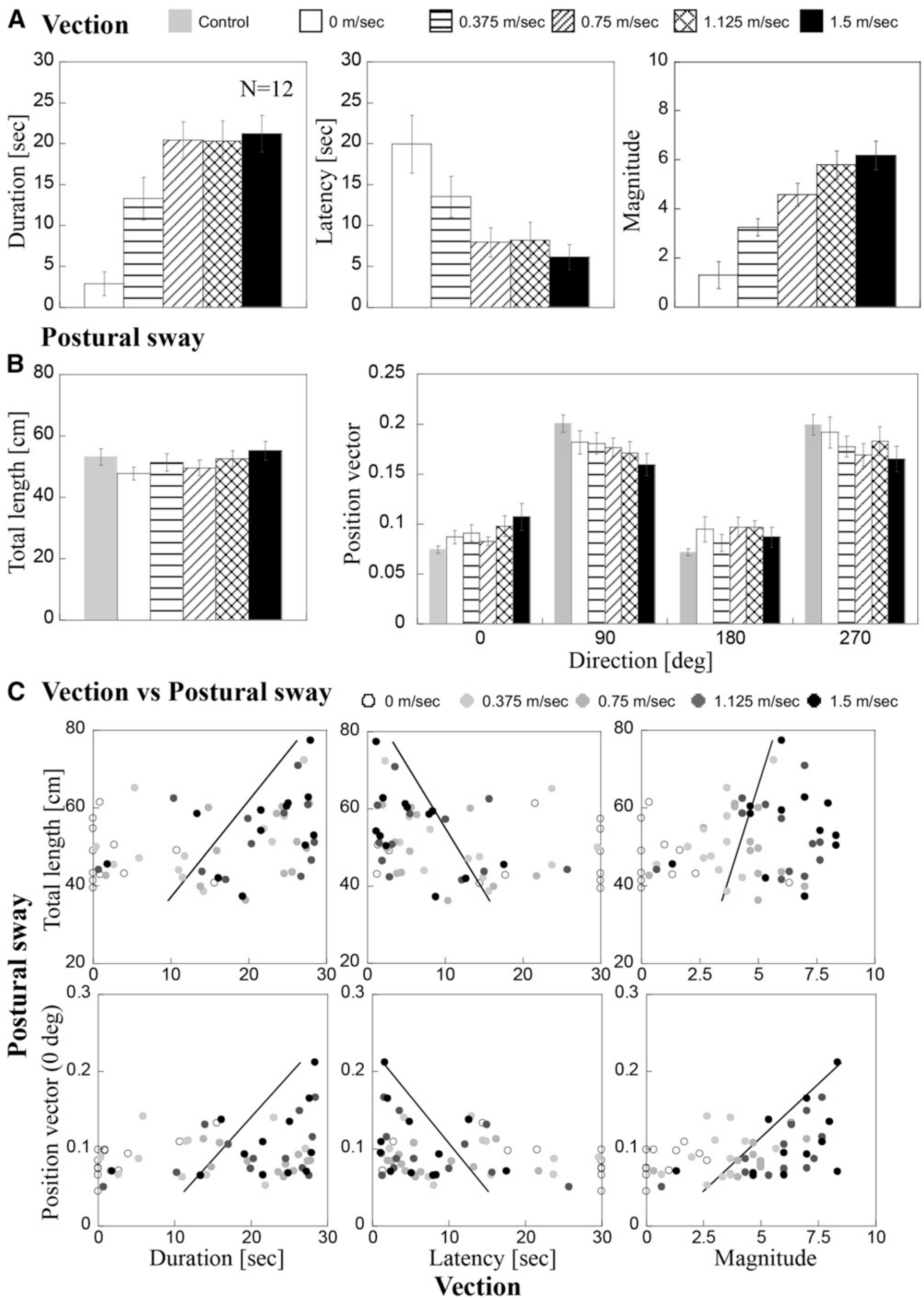

Fig. 3. The results for A) vection measurements, B) postural sway, and C) their correlation in the five speed conditions. Error bars indicate SEs. Diagonal lines represent the best-fitting regression.

direction, the vector increased as the speed of vection stimuli increased. In contrast, in the front (90°) and back (270°) directions, vectors decreased as the speed of vection stimuli increased. When the speed of vection stimuli increased, the directions of body sway appeared to change from forward and back to right and left.

A one-way ANOVA of the mean position vectors revealed a significant effect of speed in the 90° [$F(5,55) = 3.237$, $P = 0.0124$] and the 180° [$F(5,55) = 2.770$, $P = 0.0265$] directions. However, multiple comparisons did not reveal any significant difference in any directions.

Taken together, these results indicate that body sway was modulated by the speed of optic flow projected on the ground surface. The results for the three vection measures in the five visual field conditions (full field, V2, V4, H2, and H4) are shown in **Fig. 4A**. Vection duration decreased and vection latency increased as the size of the visual field decreased, e.g., when the size of the optic flow field was smaller, vection became weaker. This size effect was more prominent in the vertical than in the horizontal conditions.

The one-way ANOVA for the three vection measures revealed a significant main effect of visual field on latency, duration, and magnitude (duration: $F[4,40] = 7.556$, $P = 0.0001$, latency: $F[4,40] = 7.423$, $P = 0.0001$, magnitude: $F[4,40] = 11.904$, $P < 0.0001$). Multiple comparisons revealed significant differences in duration between Full field and V4 ($P = 0.0346$), and between V4 and H2 ($P = 0.0369$). For latency, there were significant differences between Full field and V4 ($P = 0.0221$). For magnitude, there were significant differences between Full field and V4 ($P = 0.0086$), and between V4 and H2 ($P = 0.0402$).

Fig. 4B's left panel shows the results of calculations of total length of body sway. Body sway appeared to decrease as the size of the stimulus field decreased. One-way ANOVA confirmed this main effect of size [$F(4,40) = 3.009$, $P = 0.0259$]. Multiple comparisons did not reveal any significant difference between any combinations of visual field conditions. In Fig. 4B's right panel, we present the results of the mean position vectors. In the back (270°) direction, the vector grew larger as the size of the stimulus field became smaller.

One-way ANOVA for the mean position vectors revealed significant main effects of size and position in the visual field only in the 270° direction [$F(5,55) = 2.678$, $P = 0.0454$]. Multiple comparisons did not reveal any significant difference in any of the directions. We concluded that body sway was modulated by the size and position of the optic flow projected on the ground surface.

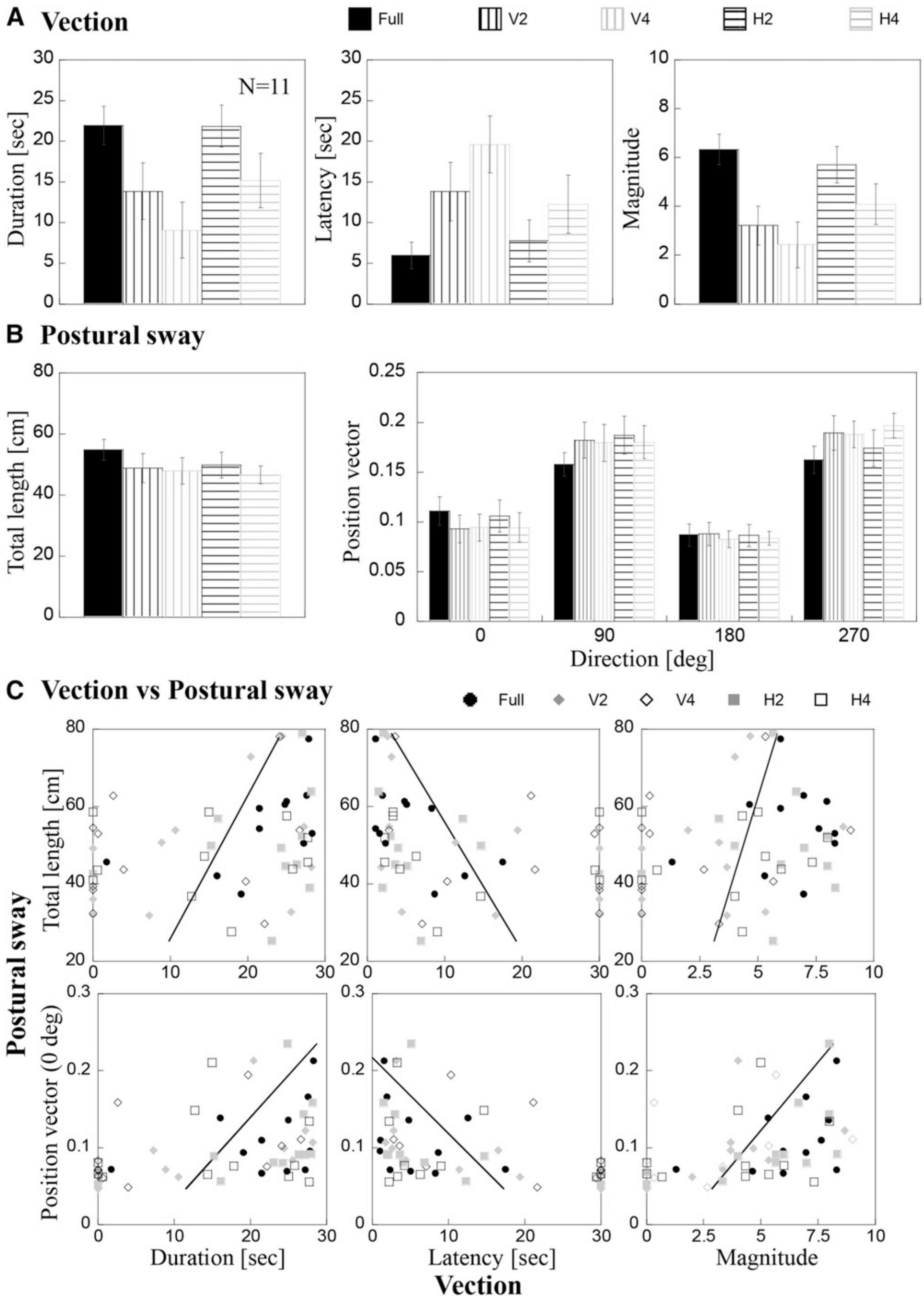

Fig. 4. The results for A) vection measures, B) postural sway, and C) their correlation in the five visual field conditions. Error bars indicate SEs. Diagonal lines represent the best-fitting regression.

The results of correlation analyses are shown in **Fig. 3C** (for the five speed conditions) and **Fig. 4C** (for the five visual field conditions). We calculated the correlation coefficients of vection measurements with total length of body sway and mean position vector in the right (0°) direction. The total length of body sway correlated significantly with vection duration (across the five speed conditions, r = 0.3628, *P* = 0.0044; across the five visual field conditions, r = 0.3201, *P* = 0.0172; thereafter, the five conditions were pooled for these analyses) and with latency (across the five speed conditions, r = −0.2959, *P* = 0.0217; across the five visual field conditions, r = −0.3569, *P* = 0.0075), but not with magnitude (across the five speed conditions, r = 0.1969, *P* = 0.1315; across the five visual field conditions, r = 0.2231, *P* = 0.1016). The mean position vector in the right direction (0°) correlated significantly with vection duration (across all speed conditions, r = 0.284, *P* = 0.0279; across all visual field conditions, r = 0.3905, *P* = 0.0032), latency (across speed conditions, r = −0.2786, *P* = 0.0311; across visual field conditions, r = −0.438, *P* = 0.0008), and magnitude (across speed conditions, r = 0.4661, *P* = 0.0002; across visual field conditions, r = 0.4523, *P* = 0.0005).

All r- and *P*-values of all correlation analyses are provided in **Table I**. The position vectors for the right (0°) and back (270°) directions were strongly correlated with vection across the five speed conditions. However, the position vectors for all directions correlated significantly with vection across the five position conditions. These results imply that the distributions of postural sway shifted from vertical (forward and back) to horizontal (right and left) as vection became stronger.

DISCUSSION

In this study, we presented vection stimuli on the ground surface and modified the stimulus dimensions of speed, size, and position to examine their effects on vection strength and on body sway. Vection strength was greater as the speed of optic flow increased (to 1.5 $m \cdot s^{-1}$). Vection latency decreased and vection duration and magnitude increased when the speed of the dots increased. This result aligns well with those of previous studies with upright stimuli, where greater vection strength was observed with increasing stimulus speed.[8,23] We can, therefore, conclude that there is a correspondence between the vection induced by ground stimuli and by upright (vertical) stimuli.

Vection strength decreased as the size of the vection stimuli on the ground surface decreased. This effect was particularly strong when the size of the stimuli was modulated in depth rather than in width. This result also corresponds well with findings on vection obtained with upright vertical stimuli:[14,26] more distant stimuli dominate the direction of vection and also induce stronger vection than do nearer stimuli.

As expected, our vection stimuli affected body sway. The total length of body sway was correlated with both vection latency and duration, but not with magnitude (Fig. 3C, Fig. 4C, and Table I). The mean position vector in the right direction was strongly correlated with vection magnitude (Fig. 3C, Fig. 4C, and Table I). This might be related to the fact that our stimuli always moved leftward. It appears that the lateral sway increased and the forward and backward sway decreased with increasing optical flow speed or size (Fig. 3B's right panel, Fig. 4B's right panel). The trend that the body sway increased along the same axis as the simulated self-motion was consistent with previous studies.[2,10,28] In this respect, our results were highly similar to those of Palmisano et al.[28]

Palmisano and colleagues'[1,29] research also indicates that individual differences in the magnitude of body sway with open eyes and closed eyes can predict vection strength. They showed that subjects with higher Romberg quotients (the ratio of body sway length with eyes closed divided by body sway length with eyes open) perceived stronger vection when smooth radial flow was presented.[29] Therefore, this kind of body sway data will be most important for our future studies and all vection studies.

Our subjects always gazed down at the fixation point on the floor. Kim and Palmisano[18] found a trend for stronger vection when gazing down (as opposed to left, right, or up). This fact might be related to our current result that almost all subjects (except one) reported relatively stronger vection. Kim and

Table I. Correlations Between Vection Measurements and Postural Sway.

	DURATION		LATENCY		MAGNITUDE	
	r	*P*-VALUE	r	*P*-VALUE	r	*P*-VALUE
Exp.1 (5 Speeds)						
Postural sway						
Total length	0.3628	*0.0044	−0.2959	*0.0217	0.1969	0.1315
0 deg (rightward)	0.284	*0.0279	−0.2786	*0.0311	0.4661	*0.0002
90 deg (forward)	−0.1229	0.3495	0.1058	0.4213	−0.3185	0.0131
180 deg (leftward)	0.0016	0.9902	0.015	0.9092	0.1896	0.1469
270 deg (backward)	−0.2922	*0.0235	0.2467	†0.0574	−0.4479	*0.0003
Exp.2 (5 Visual fields)						
Postural sway						
Total length	0.3201	*0.0172	−0.3569	*0.0075	0.2231	0.1016
0 deg (rightward)	0.3905	*0.0032	−0.438	*0.0008	0.4523	*0.0005
90 deg (forward)	−0.3639	*0.0063	0.4006	*0.0024	−0.4199	*0.0014
180 deg (leftward)	0.2818	*0.0371	−0.3056	*0.0233	0.3276	*0.0146
270 deg (backward)	−0.5119	*0.0001	0.5453	*< 0.0001	−0.5374	*< 0.0001

* *P*-value ≤ 0.05; † 0.05 < *P*-value ≤ 0.10.

Palmisano[18] also found that reductions in ocular following response velocity could predict vection improvements. Therefore, it might have also been useful to monitor eye movements as well as postural sway during self-motion stimulation in the current study. We plan to do just this in a future study. We consider this to be the next most important topic.

After the experiment, we obtained oral subjective reports from all subjects. Some reported that they perceived the optic flow on the ground surface like the flow of a river. It has been reported anecdotally that when we observe the flow of a river, we can perceive vection in the opposite direction to the flow.[21] This meaning-laden interpretation of an optic flow that was intended to be meaningless may have enhanced vection. On the Wii balance board, the eyes are positioned a little higher than usual relative to the ground. Some subjects suggested that this change in eye height may have affected vection induction.

In previous studies,[2,10,37] it has been reported that vection stimuli projected on the ground surface can induce vection. We succeeded in replicating this result. We showed that ground surface stimuli alone can induce substantial, strong vection. The stimulus properties of the ground surface were very similar to those that have been used with upright vertical stimuli in studies on the effects of size and speed of optic flow.[13,20,26]

There were some limitations in this study. The sizes and the speeds of our stimuli were restricted to a small range. In the future we would like to employ wider and also faster ground surface stimuli to determine whether these could produce more effective vection induction. Additionally, in this study, our stimuli were trapezoidal in shape. Other shapes, i.e., square or circular, should also be examined. Square shapes in particular might serve as more appropriate comparisons for the upright vertical stimuli. Furthermore, the sizes and positions of the stimulus field were determined by convenience. Other combinations should be examined in the future. These limitations notwithstanding, we believe that our method represents a valuable first step in quantitative research on vection induced by a ground surface.

In the future, we should also examine the effects of color and depth order for vection by ground surface stimuli. For example, the facilitation effect of multiple colors in vection stimuli[5] and the inhibition of vection by red[35] should be examined for ground surface stimuli. Additionally, when the stimuli on the ground surface have some depth properties (for example, floating dots in front of or behind the ground surface), vection strength may be modulated by those properties. This possibility should be examined in future work.

Finally, we would like to associate our research with "aerospace medicine and human performance." Our present results give us an important suggestion that ground surface optical flow induces strong vection in the same manner as the motion of a frontal surface. Our results should therefore also benefit flight simulation. The assessment of the effect of speed of ground optical flow should be very meaningful for some flight pilots because the pilot sees the low-speed optical flow on the ground when she/he sails in the sky. Our results showed that the low speed optical flow on the ground surface did induce weaker but substantial vection. This aspect should be further examined in the future for the safer manipulation of aircraft. Practical studies connecting vection on a ground surface with the driving skills of a helicopter will be indeed needed in the future. We hope that our study can be a stepping stone for this research.

In conclusion, stimuli on the ground surface can induce substantial vection. When stimulus speed and size increase, vection will be stronger. If stimulus size and speed are held constant, stronger vection will be obtained when the stimulus is presented farther away in the depth field.

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REFERENCES

1. Apthorp D, Palmisano S. Linear and non-linear measures of postural control predict individual variations in illusions of self-motion. Front Hum Neurosci Conference Abstract. ACNS-2013 Australasian Cognitive Neuroscience Society Conference; 2013 Nov. 28-Dec. 1; Melbourne, Australia. Melbourne (Australia): Monash University; 2013.
2. Baumberger B, Isableu B, Flückiger M. The visual control of stability in children and adults: postural readjustments in a ground optical flow. Exp Brain Res. 2004; 159(1):33–46.
3. Bian Z, Braunstein ML, Anderson GJ. The ground dominance effect in the perception of 3-D layout. Percept Psychophys. 2005; 67(5): 802–815.
4. Brandt T, Dichgans J, Koenig E. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Exp Brain Res. 1973; 16(5):476–491.
5. Bubka A, Bonato F. Natural visual-field features enhance vection. Perception. 2010; 39(5):627–635.
6. Clark RA, Bryant AL, Pua Y, McCrory P, Bennell K, Hunt M. Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. Gait Posture. 2010; 31(3):307–310.
7. Dichgans J, Brandt T. Visual-vestibular interaction: effect on self-motion perception and postural control. In: Held R, Leibowitz HW, Tueber HL, editors. Handbook of sensory physiology. Berlin (Germany): Springer-Verlag; 1978:79–230.
8. de Graaf B, Wertheim AH, Bles W, Kremers J. Angular velocity, not temporal frequency determines circular vection. Vision Res. 1990; 30(4): 637–646.
9. Fischer MH, Kornmüller AE. Optokinetisch aus-gelöste Bewegungswahrnehmungen und optokinetscher Nystagmus. Journal für Psychologie und Neurologie. 1930; 41:273–308.
10. Flückiger M, Baumberger B. The perception of an optical flow projected on the ground surface. Perception. 1988; 17(5):633–645.
11. Gibson JJ. The senses considered as perceptual systems. Boston (MA): Houghton Mifflin; 1966.
12. Gibson JJ. The ecological approach to visual perception. Boston (MA): Houghton Mifflin; 1979.
13. Held R, Dichgans J, Bauer J. Characteristics of moving visual scenes influencing spatial orientation. Vision Res. 1975; 15(3):357–365.

14. Ito H, Shibata I. Self-motion perception from expanding and contracting optical flows overlapped with binocular disparity. Vision Res. 2005; 45(4):397–402.
15. Japan Society for Equilibrium Research. Juusindouyou no Q&A, Tebiki [Q&A and road map for body sway measure]. Equilib Res. 1996; 55(1):64–77 [In Japanese].
16. Johansson G. Studies on visual perception of locomotion. Perception. 1977; 6(4):365–376.
17. Kanazawa M, Uozato H, Asakawa K, Kawamorita T. Effect of prism base direction on posture stabilization. Vision. 2012; 24(4):137–144 [In Japanese].
18. Kim J, Palmisano S. Eccentric gaze dynamics enhance vection in depth. J Vis. 2010; 10(12):7.
19. Kitabayashi T, Demura S, Noda M. Examination of the factor structure of center of foot pressure movement and cross-validity. J Physiol Anthropol Appl Human Sci. 2003; 22(6):265–272.
20. Lestienne F, Soechting J, Berthoz A. Postural readjustments induced by linear motion of visual scenes. Exp Brain Res. 1977; 28(3-4):363–384.
21. Mach E. Grundlinien der Lehre von den Bewegungsempfindungen. Leipzig (Germany): Englemann; 1875.
22. McCarley JS, He ZJ. Asymmetry in 3-D perceptual organization: ground-like surface superior to ceiling-like surface. Percept Psychophys. 2000; 62(3):540–549.
23. Melcher GA, Henn V. The latency of circular vection during different accelerations of the optokinetic stimulus. Percept Psychophys. 1981; 30(6):552–556.
24. Nakamura S. Effects of depth, eccentricity and size of additional static stimulus on visually induced self-motion perception. Vision Res. 2006; 46(15):2344–2353.
25. Ogawa M, Seno T. Vection is modulated by the semantic meaning of stimuli and experimental instructions. Perception. 2014; 43(7):605–615.
26. Ohmi M, Howard IP. Effect of stationary objects on illusory forward self-motion induced by a looming display. Perception. 1988; 17(1):5–12.
27. Ohsawa I, Uematsu H. Research of masticatory function using hemiplegia simulator equipment. Gerodontology. 2012; 29(2):e780–e786.
28. Palmisano S, Pinniger G, Ash A, Steele JR. Effects of simulated viewpoint jitter on visually induced postural sway. Perception. 2009; 38(3):442–453.
29. Palmisano S, Apthorp D, Seno T, Stapley PJ. Spontaneous postural sway predicts the strength of smooth vection. Exp Brain Res. 2014; 232(4):1185–1191.
30. Post RB. Circular vection is independent of stimulus eccentricity. Perception. 1988; 17(6):737–744.
31. Riecke BE, Schulte-Pelkum J, Avraamides MN, Von Der Heyde M, Bülthoff HH. Cognitive factors can influence self-motion perception (vection) in virtual reality. ACM Trans Appl Percept. 2006; 3(3):194–216.
32. Rushton SK, Harris JM, Wann JP. Steering, optic flow, and the respective importance of depth and retinal motion distribution. Perception. 1999; 28(2):255–266.
33. Sato T, Seno T, Kanaya H, Fukazawa H. The ground is more effective than sky – The comparison of the ground and the sky in effectiveness for vection. Proceedings of ASIAGRAPH 2007; Shanghai. Tokyo (Japan): Virtual Reality Society of Japan; 2007:103-108.
34. Seno T, Fukuda H. Stimulus meanings alter illusory self-motion (vection) – experimental examination of the train illusion. Seeing Perceiving. 2012; 25(6):631–645.
35. Seno T, Sunaga S, Ito H. Inhibition of vection by red. Atten Percept Psychophys. 2010; 72(6):1642–1653.
36. Seno T, Ito H, Sunaga S. The object and background hypothesis for vection. Vision Res. 2009; 49(24):2973–2982.
37. Trutoiu LC, Mohler BJ, Schulte-Pelkum J, Bülthoff HH. Circular, linear, and curvilinear vection in a large-screen virtual environment with floor projection. Comput Graph. 2009; 33(1):47–58.
38. Wei K, Stevenson IH, Körding KP. The uncertainty associated with visual flow fields and their influence on postural sway: Weber's law suffices to explain the nonlinearity of vection. J Vis. 2010; 10(14):4.