Orientation-defined visual rotation significantly affects observer's perceived self-motion

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It is believed that visual self-motion perception (vection) can be effectively induced only in the case where the inducer's motion is defined by luminance modulation. In this study, psychophysical experiments examining the potential effects of visual motion defined by features other than luminance on visual self-motion perception (vection) were conducted, employing orientation-defined rotation (so-called fractal rotation) as a visual inducer. The experiments clearly indicate that orientation-defined visual rotation can strongly induce an observer's perceived self-rotation (roll vection), although it was significantly weaker than that induced by luminance-defined rotation. In the case where the orientation and luminance rotations were combined and presented simultaneously, perceived self-rotation was mainly determined by the luminance rotation when both factors were set to rotate in consistent or inconsistent directions. These results suggest that feature-defined visual motion containing no luminance modulation has the potential to contribute to visual self-motion perception.

Introduction

Accurate perception of self-motion is crucial to our behavioral adaptation to the environment. In natural circumstances, many kinds of sensory information contribute to self-motion perception, including visual, vestibular, kinesthetic, and somatosensory information, and they are thought to be integrated in harmony to achieve robust spatial self-orientation (e.g., Howard, 1982; for a recent review, see Britton & Arshad, 2019). Some recent studies have revealed that auditory information also contributes to self-motion perception (e.g., Riecke, Schulte-Pelkum, Caniard, & Bülthoff, 2005; Riecke, Feuereissen, & Rieser, 2008). On the other hand, it is widely known that a uniformly moving visual stimulus that occupies a large part of the observer's field of view can induce an observer's self-motion perception in the opposite direction (Fischer & Kornmüller, 1930; for a review, see Palmisano, Allison, Schira, & Barry, 2015). This perceptual phenomenon is referred to as visually induced self-motion perception, or vection.

In vection, the observers are, in fact, static in space but perceive significant self-motion. Vection clearly indicates that visual information can effectively cause an observer's self-motion perception by itself even where there is no corresponding self-motion information from other sensory systems. Thus, vection demonstrates that visual information dominates the observer's self-motion perception. When we move through a natural visual environment, retinal images of the externally static visual objects flow in accordance with our self-motion (i.e., optic flow). Translational optic flow (either horizontal or vertical) results from translational self-motion in the opposite direction, forward or backward self-motion causes expanding or contracting flow, and rotational optic flow indicates self-rotation in the counter direction. Conversely, horizontal or vertical translational self-motion perception (linear vection) is induced by the corresponding translational optic flow. Expanding/contracting flow induces forward/backward self-motion perception (forward/backward vection), and rotational flow results in rotational self-motion perception (roll vection) if the visual inducer occupies enough of the observer's field of view. The correspondence between the optic flow as an input and self-motion perception as an output is assumed to be identical for natural self-motion in our everyday living and vection in experimental situations (Andersen, 1986).

In psychophysical vection studies, many researchers have analyzed visual factors that affect the occurrence and strength of vection in order to investigate the neural and perceptual mechanisms underlying visual self-motion perception (for a review, see Palmisano et al., 2015). These studies have accumulated important knowledge concerning visual self-motion perception. For example, a larger visual stimulus can induce stronger vection than a smaller one (Brandt, Dichgans, & Koenig, 1973; Nakamura & Shimojo, 1998). The depth structure of the visual stimulus (i.e., foreground/background relationship) significantly affects the occurrence and strength of vection (Ohmi & Howard, 1988; Howard & Heckman, 1989; Nakamura & Shimojo, 1999; Nakamura, 2006; Kim & Khuu, 2014; Palmisano, Summersby, Davies, & Kim, 2016).

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Random jitter or periodical oscillation introduced into the visual inducer has facilitative effects on vection (Palmisano, Gillam, & Blackburn, 2000; Palmisano, Kim, Allison, & Bonato, 2011; Kim & Palmisano, 2008; Nakamura, 2010). Perceived rigidity of the visual inducer possibly modulates visual self-motion perception (e.g., Nakamura, 2019), and so on. Based on these findings, researchers have proposed several psychological models of visual self-motion perception (e.g., Palmisano et al., 2015).

Most studies, including those mentioned above, have employed smooth and continuously moving visual stimuli (i.e., physical motion) as a vection inducer. In addition, it has also been shown that vection can be induced by apparent motion (i.e., the phi phenomenon) (e.g., Schor, Lakshminarayanan, & Narayan, 1984) or motion contrast (i.e., induced motion, also known as the Duncker illusion) (e.g., Howard & Heckman, 1989; Howard & Howard, 1994). For example, Nakamura (2013a) employed two- and four-stroke apparent motions as vection inducers and found that these types of apparent motion can effectively induce an observer's self-motion perception, although the strength of vection was significantly weaker than that induced by an equivalent physical motion. In the condition where two- or four-stroke apparent motion was presented, the observers perceived a continuous and unidirectional motion of the visual object without displacement of its spatial locations (perceived motion and perceived displacement of the visual inducer were dissociated in such a situation) (Anstis & Rogers, 1986; Mather, 2006). In order to induce visual self-motion perception, physical motion (or physical displacement) of the visual inducer is not required, but its perceived motion is considered essential.

On the other hand, some of the previous examinations of the effects of so-called second-order motion (i.e., feature-defined motion without first-order motion energy, such as contrast-defined motion or texture-defined motion) have failed to find a significant impact on the perception of self-motion (e.g., Gurnsey, Fleet, & Potechin, 1998; Seno & Palmisano, 2012). The second-order motion employed in these studies provided the observers a perceptual impression of visual motion with substantial strength. These results contradict the assumption that perceptual motion of the visual inducer would be sufficient to induce vection. First-order motion energy should be required for vection induction (might be a trigger), and perceived motion of the visual stimulus would modulate vection strength. Thus, in the current understanding, second-order motion would not be able to induce vection effectively by itself, even though it causes a strong visual motion perception.

Allison, Ash, and Palmisano (2014) conducted vection experiments examining the effects of stimulus depth defined by binocular disparity on visual self-motion perception. In their experiments, visual stimulus with depth corrugation defined by disparity induced stronger vection than a flat pattern. However, the advantage of the additional binocular information decreased with a shortened lifetime of dots making up the visual pattern, and self-motion could not be effectively induced in the case where random dots were refreshed in each frame (the dynamic random-dot stereogram condition). In the dynamic random-dot stereogram condition, there was no luminance-defined motion in the visual pattern, and stereoscopically defined depth carried all motion information. Their experiments indicated that visual features defined without luminance modulation significantly affect vection strength, although vection cannot be inducible in the absence of motion information modulated by luminance in some other way.

The present study further investigated the potential effects of a second-order motion signal of the visual stimulus on vection employing yet another visual stimulus—namely, orientation-defined visual rotation, known as fractal rotation (Benton, O'Brien, & Curran, 2007; Lagacé-Nadon, Allard, & Faubert, 2009). In fractal rotation, the orientation of the visual structure is set to rotate with a given velocity using a rotating orientation filter. The fractal rotation contains no luminance correlation between visual frames. Nevertheless, observers can clearly perceive a global rotation of the whole visual pattern in accordance with the visual orientation (see the Apparatus and stimulus section for details). As per the nature of fractal rotation, local rotations with the same speed and direction as the global rotation are perceptible at any given location within the pattern if a small aperture with random position is applied to it. This is a reason why Benton and colleagues termed this perceptual phenomenon "fractal."

This article reports psychophysical experiments that examined whether null findings concerning the effect of the second-order motion signal on vection also hold for the condition where the orientation-defined rotation was employed as a visual inducer.

Experiment 1

Methods

Ethics statement

The experiments reported here were reviewed and approved in advance by the Ethics Committee at Nihon Fukushi University (#14-47). A few days prior to the experimental session, all participants were informed about the content of the experiment, and they confirmed their intent to participate in the experiment with written consent.

Participants

Sixteen undergraduate students (seven males and nine females; age range, 19–22 years old) volunteered to participate in the experiment. All participants had normal or corrected-to-normal visual acuity, with no self-reported vision or vestibular impairments. Although some of them reported previously participating in vection experiments, none was aware of the purpose of the experiments.

Apparatus and stimulus

The visual stimulus was presented on a 55-inch flat-screen liquid-crystal display (HS55K20; Hisense, Qingdao, China). The participants observed the visual display through a rectangular viewing tube that limited their field of view to 60° vertical and 90° horizontal visual angle so that only the display was in their field of view at a viewing distance of 86 cm. The resolution of the display was 1920 pixels in width by 1080 pixels in height (each pixel subtended 3.07 minarc in visual angle), and the refresh rate was 60 Hz. The display had 32-bit color depth (a 256-step grayscale stimulus was employed in the experiment) and was calibrated so that the darkest pixel (intrinsic brightness value of 0) was 2.3 cd/m^2, and the brightest pixel (255 luminance) was 17.2 cd/m^2. The gamma value of the display was set to 2.2. The height of each participant's chair was adjusted to ensure that his or her eye position was aligned with the center of the screen. The experimental trials were carried out in a dark room in which the visual display was the sole light source. A personal computer (PC) equipped with an OpenGL-compatible graphics card was used for presentation of the visual stimulus. An additional mouse connected to the stimulus-generating PC was used to measure each participant's response.

The stimulus employed in this experiment was a rotating visual pattern presented in the central circular area of the display, subtending a radius of 30° in visual angle. There were two types of visual rotation: orientation-defined rotation and luminance-defined rotation. In the orientation-defined rotation condition, the so-called "fractal rotation" was used as a visual inducer. Similar to Benton et al. (2007), a fractal rotation stimulus was created as follows. First, a two-dimensional (2D), white-noise pattern, 1024 pixels in height and width, was created; the luminance of each pixel in the pattern was randomly determined from 0 to 255 with the intrinsic brightness scale of the PC (Figure 1a). The amplitude spectrum of the noise image calculated by Fourier transformation was weighted by a 2D spatial bandpass filter. The bandpass characteristic of the filter was depicted as a "line" with a designated slope on the *u*, *v* plane; the filter contained a wide passband parallel to the slope but showed a very narrow passband characteristic against an orthogonal component (Figure 1b, in which the white region indicates a weight of 1.0 and the black region a weight of 0.0). The passband was set to the Nyquist frequency (9.0 cycles per degree [cpd]) for the component parallel to the slope and decreased to 1/128 (0.07 cpd) for the orthogonal component. The filter was blurred by a Gaussian filter, for which the standard deviation was half of the width of the line-shaped filter. To eliminate the direct current component, spatial frequencies lower than 0.1 cpd were blocked by the filter (note the gap in the center of the line-shaped filter in Figure 1b). The weighted amplitude and phase were combined to create the output image by inverse Fourier transformation (phase information was kept identical to the original image).

The output of the above-mentioned filtering processing was an elongated visual image with a specific orientation orthogonal to the slope of the filter. In addition, low-pass filtering with a Gaussian filter with a standard deviation of 0.5 cpd was applied to the output image in order to suppress high-frequency noise. A peripheral annular area was masked and filled with a neutral gray with luminance set to 9.7 cd/m^2, and the target image was presented only in a central circular area of radius 30° visual angle (Figure 1c).

By rotating the slope of the filter, the orientation of the resulting image was also rotated (Figure 1, lower column). The initial orientation of the filter (and thus also the initial orientation of the visual pattern) was randomly determined. In the orientation-defined motion stimulus employed in this experiment, the original random noise pattern was newly created for each frame, and the slope of the filter was rotated (either clockwise or counterclockwise) at a given speed. By integrating the output visual images across frames, a visual sequence in which the orientation of the visual pattern was smoothly rotated with a given speed (i.e., fractal rotation) was obtained. In the fractal rotation stimulus employed in this experiment, the original noise image was refreshed by each frame, and the filtering process was completed within the frame. Therefore, there was theoretically no luminance-defined motion energy in the visual sequence. In fact, it was confirmed that the visual stimuli employed in the experiment contained luminance correlation in neither the translational nor the rotational direction between each successive two frames. The observer nevertheless perceived unidirectional rotation of the global visual pattern through the modulation of the visual orientation.

In the luminance-defined rotation condition, a single visual frame was randomly selected from the fractal rotation sequence and physically rotated

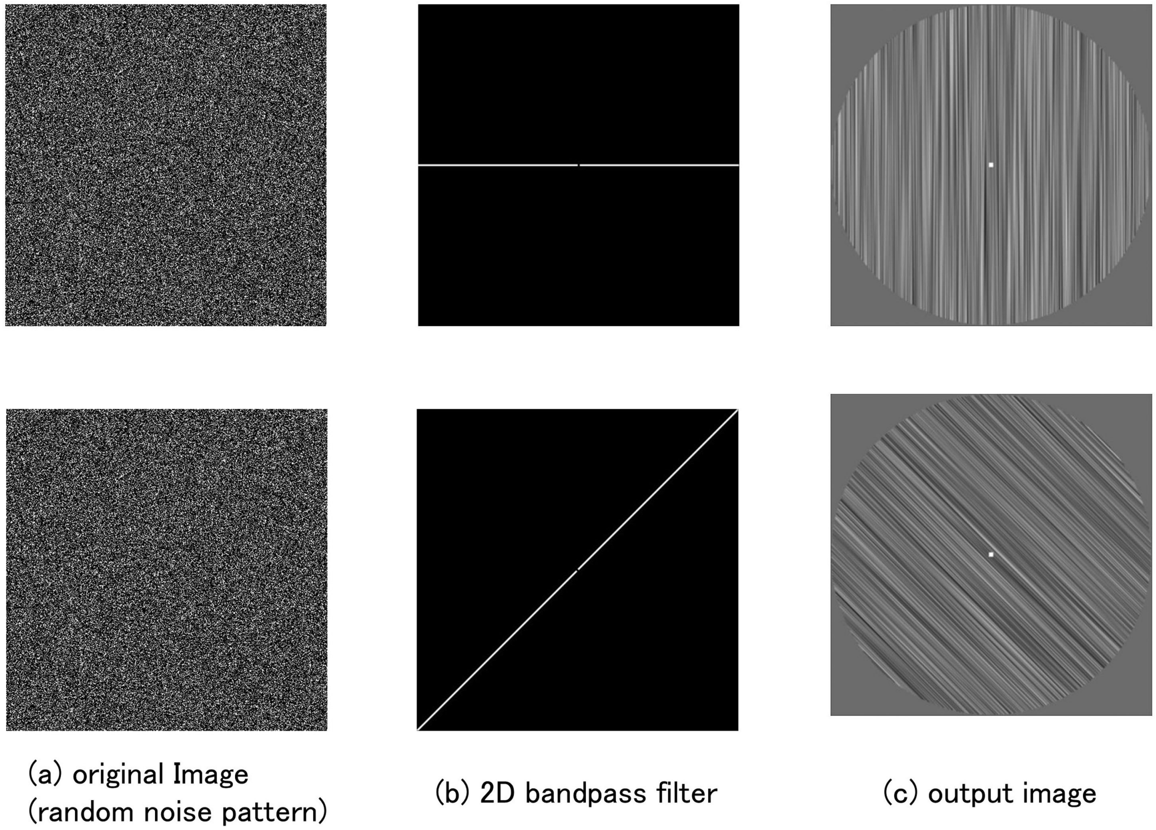

Figure 1. Procedure to create orientation-defined rotation (fractal rotation). (a) Original image (random noise pattern), (b) 2D bandpass filter, and (c) output image of the filter. The orientation of the visual components in the output image rotates with the rotation of the 2D bandpass filter. There was no luminance correlation between frames.

at a given speed. In both of the stimuli employed in this experiment (the orientation-defined and luminance-defined rotations), a white fixation spot with a size of 0.5° was added to the center of the display. The luminance histogram was adjusted so that the luminance of the brightest pixel was 17.2 cd/m^2, that of the darkest pixel was 2.3 cd/m^2, and the mean luminance was 9.7 cd/m^2. By controlling the mean luminance to be equal across frames, luminance flickering was minimized in the orientation-defined motion condition. The image processing procedure described here was conducted using MATLAB and Image Processing Toolbox (MathWorks, Natick, MA). See Supplementary Movies S1, S2, S3 and S4.

Procedure

All participants were instructed to observe the moving stimulus presented on the display through the viewing tube attached to the immobile frame, fixating their eyes on the static fixation spot. Participants held their head as static as possible during observation with the viewing tube. The task of each participant was to observe the visual stimulus and report the perceived self-rotation by pressing a mouse button corresponding to the direction of the perceived self-rotation when they perceived their body to be rotating and holding the mouse button down while the self-rotation perception continued. It was emphasized that they had to stop pressing the button immediately when the self-rotation perception ceased and then press it again when the vection resumed. Additionally, after each trial, all participants were required to estimate the strength of the perceived self-rotation experienced during the stimulus presentation via a magnitude estimation method for the vection experienced with the standard stimulus as a modulus (a strength estimate of 50 was assigned for the self-rotation perceived with the standard stimulus). The standard stimulus was identical to the stimuli used for luminance-defined rotation with a speed of 30°/s. At the beginning of the stimulus presentation, a static version of the visual stimulus was presented for 5 seconds, followed by 30 seconds of stimulus rotation, and then the stimulus disappeared.[1] A white noise pattern was presented for 5 seconds after the rotating stimulation was terminated to prevent motion adaptation. The direction of rotation (clockwise or counterclockwise) was randomly determined in each trial to avoid adaptation.

There were four different stimulus conditions in total: two rotation types (orientation-defined rotation or luminance-defined rotation) and two rotational speeds (30°/s and 60°/s). The experimental trials for each condition were repeated five times in a randomized order; therefore, each participant underwent 20 experimental trials. Prior to the experimental trials, each participant observed the standard stimulus to establish a modulus strength for the estimation and to become familiar with the experimental procedure.

The time interval between trials was longer than 60 seconds (including the time needed for strength estimation) to avoid observer fatigue and motion after effects. Moreover, all participants could rest or observe the standard stimulus again upon request whenever needed. After all vection trials, the participants were asked to review the visual stimulus in order to evaluate the perceived smoothness of its rotational motion. The modulus for the smoothness evaluation was the same for vection strength estimation (the luminance-defined rotation with a rotational speed of 30°/s), and an evaluation value of 50 was assigned for the smoothness with this control condition. The stimulus duration was also 30 seconds. The smoothness evaluation was repeated three times in a randomized order.

All participants conducted all the trials within a single day, and the experiment took approximately 60 minutes to complete.

Experimental design

There were two independent variables in this experiment. The first was the type of rotation of the visual stimulus. The two different types of rotation were orientation-defined rotation and luminance-defined rotation, as described earlier. The second variable involved the rotational speed of the visual stimulus, which was manipulated at two levels: 30°/s or 60°/s. The refresh rate of the visual display was 60 Hz, so the displacements of the orientation between visual frames were 0.5° and 1.0°, respectively.

In this experiment, four different dependent variables were adopted: three vection strength indices (i.e., latency, duration, and estimated strength) and perceived smoothness of the visual stimulus. Onset latency and accumulated duration were calculated based on the participants' button-pressing responses. Stronger vection tends to have shorter latency, longer duration, and higher strength estimates. In most trials, the participants experienced self-rotation perception in the direction opposite that of the visual stimulus, and its latency, duration, and strength estimate varied depending on the stimulus conditions. In exceptional cases where no vection was reported, latency was assigned a value of 30 seconds (the same as the stimulus duration), and the duration and estimation were 0. There were no trials where the participant reported that their self-body was rotated in the same direction as the stimulus rotation. Each independent variable was averaged across trials for each experimental condition for each participant. The estimated strength of vection and the smoothness evaluation of the inducer were converted into the ratios against those experienced with the standard stimulus. Two-way repeated-measures analyses of variance (rANOVAs) with a 2 (types of rotation) × 2 (rotational speeds) factorial design were independently applied for the three vection indices and smoothness evaluation. The minimum significance level was set to 5%.

Results and discussion

rANOVAs revealed a significant main effect of the type of rotation for the three vection indices: latency, $F(1, 15) = 16.49$, $p = 0.001$, $\eta^2{}_p = 0.52$; duration, $F(1, 15) = 21.49$, $p < 0.001$, $\eta^2{}_p = 0.59$; strength estimate, $F(1, 15) = 13.80$, $p = 0.002$, $\eta^2{}_p = 0.48$. The main effect of the rotational speed did not reach the minimum significance level for any vection index: latency, $F(1, 15) = 0.23$, $p = 0.67$, $\eta^2{}_p = 0.015$; duration, $F(1, 15) = 3.40$, $p = 0.085$, $\eta^2{}_p = 0.18$; strength estimate, $F(1, 15) = 1.62$, $p = 0.22$, $\eta^2{}_p = 0.098$. In addition, there was no significant interaction between the type of rotation and rotational speed: latency, $F(1, 15) = 1.02$, $p = 0.33$, $\eta^2{}_p = 0.064$; duration, $F(1, 15) = 0.32$, $p = 0.58$, $\eta^2{}_p = 0.021$; strength estimate, $F(1, 15) = 1.44$, $p = 0.25$, $\eta^2{}_p = 0.088$. Figure 2 shows vection strength indices averaged across participants under each stimulus condition (a, vection onset latency; b, accumulated vection duration; c, vection strength estimate). Latency was shorter, duration was longer, and the strength estimate was higher in the luminance-defined rotation condition than in the orientation-defined rotation condition. Thus, the three vection indices consistently indicate that vection induced by the visual stimulus with luminance-defined rotation was significantly stronger than that induced by orientation-defined rotation. On the other hand, vection with significant strength was still induced even by orientation-defined rotation, although it was weaker than that induced by luminance-defined rotation; the duration and strength estimates in the orientation-defined rotation condition were roughly half those in the luminance-defined rotation condition. Therefore, it can be concluded that fractal rotation, which was tested as a potential vection inducer in this experiment, can evoke an observer's visually induced self-rotation perception with substantial strength, even though it contains no luminance correlation between the frames. To the best of our knowledge, this is the first report that second-order motion (feature-defined motion) can induce vection with strength

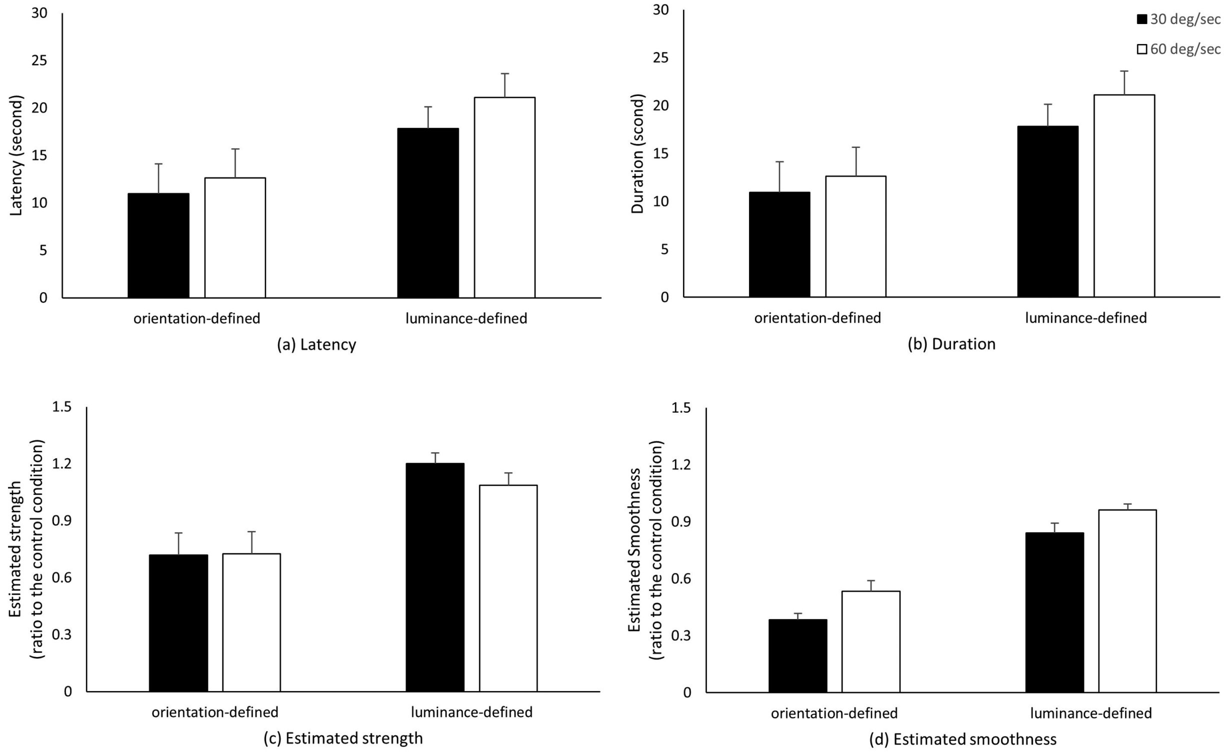

Figure 2. Vection strength indices and smoothness evaluation obtained in Experiment 1 by rotational type (orientation-defined or luminance-defined rotation) and rotational speed (30°/s or 60°/s). (a) Latency, (b) duration, (c) estimated strength of vection, and (d) estimated smoothness of the visual inducer. Error bars indicate standard errors of the mean.

comparable to the case where first-order motion (luminance-defined motion) was employed as a vection inducer.

Figure 2d shows the averaged results of the smoothness evaluation under each stimulus condition. rANOVA revealed significant main effects of rotation type, $F(1, 15) = 78.62$, $p < 0.001$, $\eta^2_p = 0.84$, and rotational speed, $F(1, 15) = 5.63$, $p = 0.03$, $\eta^2_p = 0.27$. The luminance-defined rotation was evaluated as being smoother than the orientation-defined rotation, and the smoothness evaluation in the faster rotation condition was higher than in the slower rotation condition. There was no significant interaction between the two main effects: $F(1, 15) = 0.44$, $p = 0.52$, $\eta^2_p = 0.029$. As seen in the Supplementary Movies, the orientation-defined rotation employed in this experiment inevitably gave the observers a "flickering" impression that might have resulted in lower perceived smoothness, which would be one of the reasons why orientation-defined rotation only induced weaker vection than luminance-defined rotation. This is plausible because previous vection studies have shown that vection strength varies as a function of the perceived smoothness of the visual inducer; degraded visual smoothness impairs perceived self-motion (e.g., Nakamura, 2013a). Nakamura (2013b) also showed that roll vection was severely impaired when the visual inducer was less smooth and confirmed that roll vection was more frangible against the degraded smoothness of the visual inducer than other types of vection. The smoothness perception, however, cannot be a primary factor in determining vection strength in this experiment because there was a discrepancy in the effects of the speed of the rotation between vection strength and smoothness perception.

Experiment 1 failed to find significant effects of the rotational speed of the visual inducer. This might be inconsistent with previous vection studies that showed that vection strength increased linearly with the inducer's speed (e.g., Sauvan & Bonnet, 1993; Sauvan & Bonnet, 1995; Nakamura & Shimojo, 1999). In this experiment, the rotational speed was manipulated at only two levels (30°/s and 60°/s), which might be insufficient to detect a significant effect of the speed on vection strength.

Experiment 2

Purpose

Experiment 1 revealed a significant contribution of orientation rotation to visually induced self-motion perception. In order to further evaluate the effects of the orientation rotation, Experiment 2 introduced a novel stimulus setting in which orientation-defined and luminance-defined rotations whose directions were either mutually consistent or inconsistent were simultaneously presented with different luminance contrast combinations.

Methods

The visual stimulus employed in this experiment was created by combining orientation-defined and luminance-defined rotations similar to those used in Experiment 1 with various luminance contrasts (hereafter, the stimulus conditions in which the luminance and the orientation rotations were combined and added with each other in a weighted sum when formulating the visual stimulus are referred to as "experimental conditions"). The luminance of both patterns was decreased to the designated levels and then summed under the experimental conditions. There were three different luminance combinations. For example, the orientation-defined rotation with its luminance level decreased by 30% (as compared with the original pattern) and the luminance-defined rotation with its level decreased by 70% were added to create a luminance combination condition of 30/70. Conditions of 50/50 and 70/30 were also prepared. The direction of rotations was also manipulated as another independent variable for two levels—namely, the consistent condition (the orientation-defined and luminance-defined rotations were in the same direction) and the inconsistent condition (both rotations were in the opposite direction with each other) in the experimental conditions. The initial angles assigned for the orientation and luminance rotations were shifted 90° from each other. See the Supplementary Movies for the visual stimuli used in the experimental conditions. There were also two different control conditions in which only the orientation-defined rotation or the luminance-defined rotation were presented (orientation control and luminance control conditions, respectively). Luminance levels in the two control conditions were also manipulated for three levels: 30%, 50%, and 70%. The rotational speed of the visual stimulus was always 30°/s in both the experimental and the control conditions.

The apparatus and procedure to measure vection strength were identical to those in Experiment 1 with the following exceptions. Only duration was measured as the dependent variable, because the results of Experiment 1 showed that the three vection indices employed there (latency, duration, and strength estimates) were mutually highly consistent. Smoothness evaluation was also not conducted in this experiment in order to simplify the procedure and shorten the experiment. Twelve undergraduate volunteers (four males and eight females; age range, 20–23 years old) who did not participate in Experiment 1 participated as observers in this experiment.

Experimental design

Similar to Experiment 1, the average duration of vection was calculated. Two-way rANOVA with a 3 (30/70, 50/50, and 70/30 luminance combinations) $\times$ 2 (consistent and inconsistent motion directions) factorial design and post hoc multiple comparisons were performed to analyze the data in the experimental conditions. A separated two-way rANOVA was also applied for duration in the control conditions with a 3 (30%, 50%, and 70% luminance levels) $\times$ 2 (orientation and luminance controls) factorial design. Planned comparisons were conducted in order to test the differences between the experimental and control conditions with identical luminance levels. The minimum significance level was set to 5%.

Results

Results of the experimental conditions

In the trials in which the participants reported that they perceived roll vection, its direction was consistent with, thus opposite to, the direction of the luminance-defined rotation, even in the inconsistent rotation condition where the luminance-defined rotation and the orientation-defined rotation were set to rotate in directions contrary to each other. In approximately 15% of the trials in the inconsistent rotation condition, the participants never reported vection (a duration of 0 seconds was assigned to such trials). rANOVA showed a significant main effect of the luminance combinations: $F(2, 22) = 42.49$, $p < 0.001$, $\eta^2_p = 0.79$. The main effects of motion direction and interaction among the independent variables were not significant: $F(1, 11) = 1.72$, $p = 0.22$, $\eta^2_p = 0.16$; $F(2, 22) = 1.10$, $p = 0.35$, $\eta^2_p = 0.091$, respectively. Figure 3a shows the average duration of roll vection measured in each experimental condition. In the luminance level conditions of 50/50 and 70/30, the duration of vection was relatively longer, approximately 20 seconds during the 30 seconds of stimulus duration, indicating that stronger vection was induced in these conditions regardless of the motion direction conditions. In the luminance level condition of 30/70, on the other hand, perceived self-rotation was weaker, as indicated by a shorter duration (approximately 7–10 seconds). Together with the above-noted finding that roll vection was induced consistently with the direction of the luminance-defined rotation, the results of the experimental conditions suggest that vection is

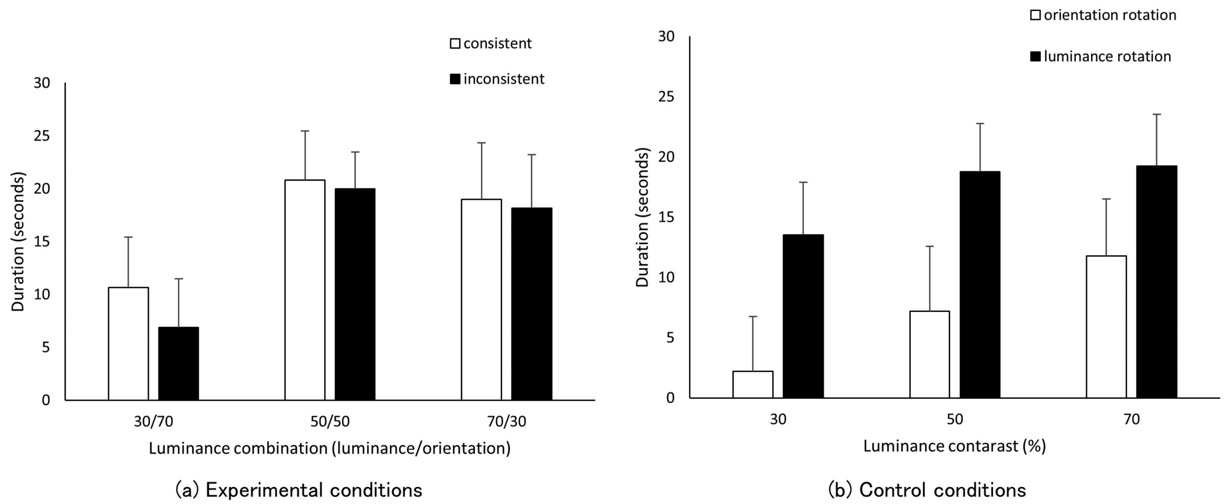

Figure 3. Vection durations under experimental and control conditions in Experiment 2. (a) Vection duration as a function of the luminance combinations under the experimental conditions. (b) Vection duration as a function of luminance contrast under the control conditions. Error bars indicate standard errors of the mean.

dominated by the luminance rotation, and stronger vection can be induced if luminance-defined rotation with a higher luminance level (higher than 50%) is presented.

Results of the control conditions

Figure 3b shows the average duration of roll vection in the control conditions. The duration of vection was longer in the luminance control than in the orientation control condition and increased with increasing luminance levels. rANOVA found significant main effects of control type, $F(1, 11) = 82.63$, $p < 0.001$, $\eta^2_p = 0.88$, and luminance level, $F(2, 22) = 19.18$, $p < 0.001$, $\eta^2_p = 0.64$, but there was no significant interaction between them, $F(2, 22) = 1.70$, $p = 0.21$, $\eta^2_p = 0.13$. Post hoc analyses using Tukey's honestly significant difference (HSD) tests indicated that there were significant differences in duration between the luminance and the orientational controls in each luminance level condition. In the orientation control condition, there were significant differences in duration between each luminance level condition. On the other hand, in the luminance control condition, significant differences were only confirmed between luminance conditions of 30% and 50% and between 30% and 70%, but the difference between the 50% and 70% conditions was not significant. Furthermore, single-tailed *t*-tests with Bonferroni correction indicated that the durations of vection were significantly higher than 0 seconds in all conditions, other than that of orientation control with a luminance level of 30%.

The results for the control conditions replicated the results of Experiment 1 and revealed that orientation-defined rotation could induce an observer's perceived self-rotation when it was presented by itself as a visual inducer (in cases where the luminance level was higher than 50%), whereas its strength was significantly weaker than that induced by the luminance-defined rotation. The strength of vection was a function of the luminance level of the visual stimulus; vection strength increased with luminance contrast. This is consistent with previous studies that used luminance-defined motion as a visual inducer (e.g., Sauvan & Bonnet, 1993). Tolerance against decreased luminance contrast was greater for luminance-defined rotation than for orientation-defined rotation, because orientation-defined rotation could not effectively induce vection in the luminance level condition of 30%, but luminance-defined rotation could still induce significant vection with the same luminance level.

Comparison between experimental and control conditions

As described above, the results of this experiment indicate that observers' visually induced self-rotation perception was dominated by the luminance-defined motion of the visual stimulus. In order to further examine the additional effects of the orientation-defined rotation, the results of the experimental conditions (both consistent and inconsistent direction conditions) were compared with the luminance control condition in which the luminance levels of the luminance-defined rotation were identical. Figures 4a and 4b compare the vection duration in the consistent and inconsistent direction conditions with the luminance control condition, respectively. Planned comparisons using *t*-tests with Bonferroni corrections showed a significant difference in duration between the inconsistent

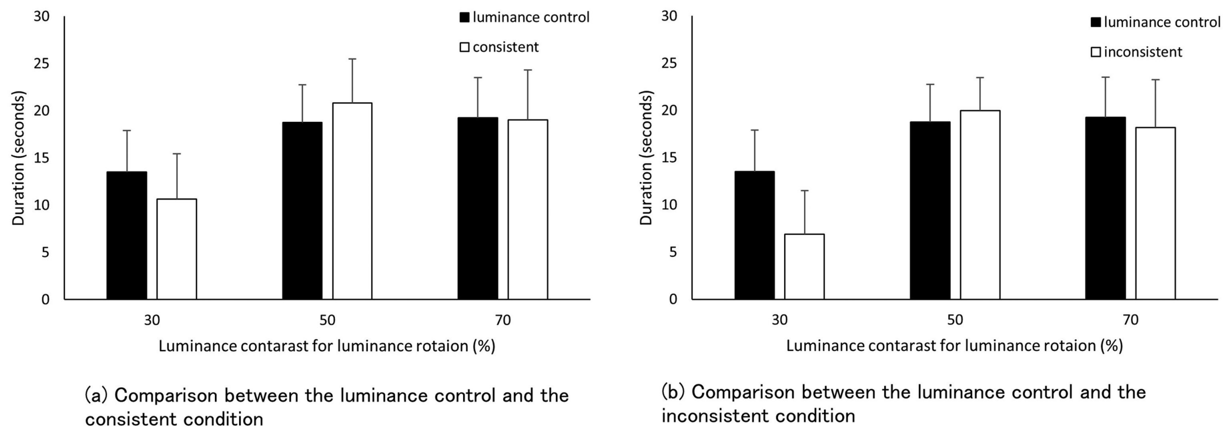

Figure 4. Comparisons of vection duration between the experimental and the luminance control conditions. (a) Comparison between the luminance control and consistent conditions. (b) Comparison between the luminance control and inconsistent conditions. Error bars indicate standard errors of the mean.

condition and the luminance control condition only for a luminance level of 30%, $t(11) = 4.17$, $p = 0.002$ (the p value indicates original probability; please note that the minimum significance level was reduced to 0.0083 due to Bonferroni corrections). No significant differences between the inconsistent direction condition and the luminance control condition were found in the other luminance level conditions, 50%, $t(11) = 0.87$, $p = 0.40$; 70%, $t(11) = 0.49$, $p = 0.64$, nor in the comparison between the consistent direction condition and the luminance control condition with all luminance levels: 30%, $t(11) = 2.03$, $p = 0.067$; 50%, $t(11) = 0.55$, $p = 0.59$; 70%, $t(11) = 0.14$, $p = 0.89$. The analyses indicate that the orientation-defined rotation had an inhibitory effect on visual self-rotation perception only in the case where it was combined with the inconsistent luminance-defined rotation with a specific luminance level combination: 30% luminance rotation and 70% orientational rotation. There was an asymmetry in the effect of the orientational rotation; there was no facilitation in the consistent direction condition (as compared with the luminance control condition) with the same luminance combination.

Discussion

Effects of second-order visual motion on self-motion perception

As described in the Introduction, previous vection studies have repeatedly reported that second-order visual motion does not have a significant impact on self-motion perception and have concluded that first-order motion energy is essential for vection (e.g., Gurnsey et al., 1998; Seno & Palmisano, 2012). On the other hand, Experiment 1 clearly indicates that orientation-defined rotation can induce an observer's self-motion perception with considerable strength, even when there is no luminance modulation in the visual inducer. One of the biggest differences between the present study and the previous ones is the type of visual inducer employed in the respective psychophysical experiments. The aforementioned studies employed contrast-defined visual motion as a second-order visual inducer. In the case of the contrast-defined motion, there would be a perceptual depth segregation; the observer commonly perceives the second-order visual motion as a semitransparent layer (like a wedding veil) moving in front of the immovable carrier. On the other hand, in the case of the orientation-defined rotation employed in the present investigation, there was no perceived depth modulation in the visual inducer. Previous vection studies have repeatedly indicated that the perceptual background dominates an observer's visual self-motion perception, and the perceptual foreground cannot effectively induce vection by itself (Ohmi & Howard, 1988; Nakamura & Shimojo, 1999). In particular, a moving foreground presented in front of a static background barely induces effective self-motion perception (Nakamura, 2006). Perceptual depth could be one of the reasons why previous research using contrast-defined motion failed to find the possible effects of second-order motion on self-motion perception.

There might be another possible factor that should be discussed here. Large-field visual stimuli that represent a specific global orientation can affect an observer's subjective verticality even when the visual stimulus remains static (as opposed to moving in the orientation-defined rotation analyzed in this article), just as in the case of the widely known rod-and-frame illusion (e.g., Witkin & Asch, 1948; Zoccolotti, Antonucci, Goodenough, Pizzamiglio, & Spinelli, 1992). Thus, one may consider that the effects of orientation-defined rotation confirmed in the present study were not due to perceived rotation of the visual inducer but rather to successive variation of the visual orientation per se. Successive variation of static visual orientation would affect the observer's subjective verticality, which might be integrated into continuous self-rotation perception. In addition, some recent vection studies have shown that the material qualities of the visual stimulus significantly affect vection strength by manipulating a complex visual texture mapped on the inducer (e.g., Kim, Khuu & Palmisano, 2016; Morimoto, Sato, Hiramatsu & Seno, 2019). The motion of visual surfaces with a complex texture might coincidentally evoke higher order motion signals along with its luminance motion. Future studies should be carried out in order to further examine these issues.

Interactions between the luminance-defined and orientation-defined rotations

Experiment 2 indicated that the orientation-defined rotation could not significantly affect self-motion perception when it was simultaneously presented with the luminance-defined rotation, which was set to rotate either in the same or in the opposite direction. Experiment 1 (and the control condition in Experiment 2) showed that orientation-defined rotation can effectively induce roll vection when it is presented by itself. Thus, the present results suggest that self-motions evoked by the luminance and the orientation rotations are not simply integrated in generating an observer's perception as an output. Instead, there would be a kind of switching mechanism, and the observer's self-motion perception would be exclusively determined by the luminance rotation when it was presented because the luminance-defined visual motion can provide a reliable frame of reference in self-motion perception. Orientation-defined rotation can be effective only when there are no other cues for self-orientation.

In the exceptional case where the luminance contrast assigned for the luminance rotation was quite low, that for the orientation rotation was sufficiently high, and they rotated in opposite directions (i.e., the inconsistent direction condition with the luminance combination of 30/70 in Experiment 2), the orientation-defined rotation significantly inhibited vection duration over that induced by the luminance-orientated rotation. The orientation-defined rotation with high luminance contrast might function as a "noise" that disturbs self-motion perception induced by the luminance-defined rotation. Self-motion perception induced by low-contrast luminance rotation would be originally weak, and the inhibition caused by the orientation rotation can be overtly confirmed in such a condition. The orientation rotation in the direction consistent with the luminance rotation did not significantly affect self-motion perception even with the same luminance combinations. The inhibitory effect emerged only in the case where the rotational directions were opposed between the different types of rotations. The same directional orientation rotation is presumably not interpreted as "noise" in the perceptual system. This might be related to a previous study (Nakamura, 2015) that observed asymmetrical effects of local rotations of visual elements introduced into a globally rotating visual pattern; the local rotation in the direction opposite the global rotation significantly inhibited the roll vection induced by the global rotation, but local rotations in the same direction as the global rotation had no effect on roll vection (there was no facilitation or inhibition compared with the baseline strength obtained under the condition of no local rotation). As described in the Introduction, the fractal rotation coincidentally evoked local orientation rotations in the same direction as the global rotation at any given region within the entire visual pattern. The contributions of the local rotations to the roll vection might be responsible for the current results, at least in part.

In future studies, the interactions between luminance and orientation rotations on self-motion perception should be examined by manipulating stimulus attributions other than the luminance contrast (e.g., rotational speed, stimulus area) independently for both types of rotation.

Conclusions

The current psychophysical experiments sought to examine the effects of visual motion defined otherwise than luminance modulation on the observer's visually induced self-motion perception. The results indicate that orientation-defined visual rotation can effectively induce the observer's roll vection in the opposite direction when presented by itself (Experiment 1). On the other hand, when orientation-defined rotation was presented with luminance-defined visual rotation, vection was mostly determined by the luminance rotation, and the orientation-defined rotation was not effective (Experiment 2).

The present study discovered the important effect of a second-order motion signal on visual self-motion perception by applying orientation-defined visual rotation (so-called fractal rotation) as a vection inducer. Using a similar method to create fractal rotation, we can make other feature-defined visual motions that contain no luminance modulation. For example, Schrater, Knill, and Simoncelli (2001) reported that when 2D bandpass filtering was applied to a random-dot visual pattern and its cutoff frequency was continuously manipulated (the passband of the filter was designed in the form of a "concentric circle" in the frequency domain, and the inner and outer radii of the filter were linearly dilated), observers perceived continuous expansion of the visual pattern, even though there was no luminance correlation between each frame (i.e., stochastic expansion). If we were to test whether a stochastic expansion can induce an observer's forward self-motion perception, we could discriminate whether the significant effects of the feature-defined motion on vection were limited to rotational self-motion or were also applicable to other types, including translational self-motion. Including the visual stimulus employed in the present investigation, visual motion without luminance modulation is quite artificial, and observers barely experience such visual motion in the circumstances of daily life. Nevertheless, future trials to examine the effects of second-order motion on visual self-motion perception should contribute to a better understanding of the perceptual mechanism responsible for our spatial orientation and self-motion perception, constituting a unique tool to investigate them. The outcomes of such trials would also be applicable to developing special effects to enrich computer graphics or animation.

Keywords: vection, visual self-motion perception, second-order motion, fractal rotation

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Footnote

[1]The static initial stimulus was a "frozen frame" created without refreshing the noise pattern even under the orientation rotation condition. The static frames could provide a strong frame of reference for the observer's self-orientation against the gravitational vertical and might function as an inhibitor of roll vection. Artefacts of the initial static stimulus would be negligible in the results, however, because there was no difference between the conditions.

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Supplementary Materials

Supplementary Video S1. Luminance-defined rotation (exp1).
Supplementary Video S2. Orientation-defined rotation (exp1).
Supplementary Video S3. Consistent-directional rotation (exp2).
Supplementary Video S4. Inconsistent-directional rotation (exp2).