Analysis of the Mixture of Linear and Circular Vections in Immersive Visual Space

Comparison of Forward and Backward Moving Visual Stimuli

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Abstract. Vection is a visually induced, self-motion illusion caused by observing a moving pattern in certain direction. Vection is classified into two types based on its moving direction: linear vection (LV; rectilinear motion sense) and circular vection (CV; rotational motion sense). Most studies focus on either LV or CV, and the mutual effects between LV and CV remain uninvestigated. Therefore, in this study, we aim to reveal the relationship between LV and CV by analyzing; whether or not each vection was perceived independently from visual stimuli with a spiral motion. From the results of our two experiments, we demonstrate that, as vection in one direction that is perceived from a visual stimulus with the spiral motion is strengthened, the vection in another direction is weakened. In other words, the strengths of both LV and CV have a negative correlation. Additionally, we explain that the influence degree of LV strength on the evaluation of CV is different between backward and forward LV.

Keywords: User interface · Ego-motion · Optic flow

1 Introduction

Vection is a visually induced, self-motion illusion caused by observing a moving pattern in a certain direction [1]. For instance, when a train on the opposite track begins to move, an observer inside a stationary train perceives his/her own train as moving in the opposite direction [2]. When the participants observed radial optic flow (Fig. 1(a)), they perceived their bodies as moving backward or forward (linear vection [LV]); when they observed rotational optic flow (Fig. 1(b)), they perceived as their bodies rotating (circular vection [CV]).

Vection can be used to express and produce rectilinear and rotational motion sense without actually moving. For this reason, many videos are designed to induce vection.

M. Kurosu (Ed.): HCII 2019, LNCS 11567, pp. 494–505, 2019.
https://doi.org/10.1007/978-3-030-22643-5_39

Discovering features to produce stronger vection or elucidate its mechanism improve its expression and immersion in videos.

Some previous studies investigated the relationship between the velocity of visual stimulus's motion and the vection strength. Berthoz et al. [3] demonstrates that the faster the linear velocity becomes, the stronger the strength of LV becomes based on the analysis of the relationship between the radial forward movement velocity of a visual stimulus and the LV strength. Similarly, Held et al. [4] explains that CV becomes stronger as the rotational velocity of a roll rotating stimulus increases. These studies reveal that the vection strength is related to the velocity of the corresponding movement in the visual stimulus; however, these studies used visual stimuli that had either linear motion or rotational motion (i.e., Fig. 1(a) or (b)).

Some studies have analyzed vection with a stimulus moving spirally, where the radial and circular movement were presented simultaneously (see Fig. 1(c)) [5–7]. For example, Palmisano et al. examined the influence of the presentation methods of visual stimuli with radial, circular of roll rotation, and spiral motions on the vection's strength. The authors measured the vection strength with one question that inquired into the overall strength of the of self-motion feeling.

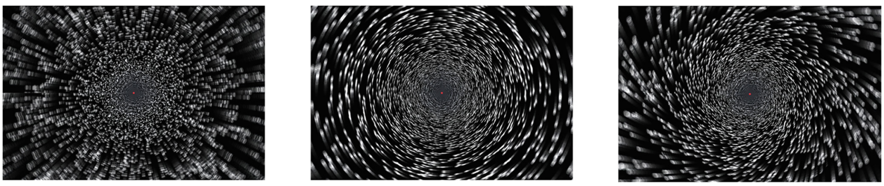
The spiral motion contains both radial and rotational movement and the velocity of each movement can be manipulated independently. An observer can perceive the linear and rotational self-motions from such a stimulus; therefore, each strength varies according to the velocity of the corresponding movement direction.

Meanwhile, whether the velocities of each movement influences the strength of vection for the no-corresponding direction remains uninvestigated-namely, the effect of the linear movement's velocity on the CV strength and vice versa. We aim to demonstrate the mutual effects of LV and CV using spiral motion stimuli (Fig. 1(c)). Additionally, we compare the effects of LV on CV strength wherein the linear motion is forward and backward.

2 Experimental Setup

2.1 Wide-Field-of-View Display System

A human's viewing angle is more than 180° in the horizontal direction. Therefore, it is important to present a visual stimulus in the participants' entire visual field investigate



(a) Radial motion (b) Circular motion (c) Spiral motion (combined radial and circular)

Fig. 1. Image of movement of visual stimulus

vection. In this study, we construct an immersive display system to present a visual stimulus to participants' entire fields of view.

The 360-degree-view videos can be presented using three projectors. The projector light dazzled participants' eyes and casted their shadows on the screen because our display system uses front projection. To solve these problems, we projected a black circle on each participant's head position, meaning the projector provided no direct light to participants' eye [8]. The participants observed the visual stimulus from a certain upright position to prevent their shadows from appearing on the screen (Fig. 2).

2.2 Visual Stimulus

In our experiments, we used a flow of random dots. This method is used in many vection studies, and participants can recognize both radial and circular motions of the visual stimulus. The vection strength is influenced by the visual stimulus's depth information [7]. Therefore, we prepared a virtual cylinder with a random dot image and moved it into the rectilinear and rotational directions, for which Fig. 3 illustrates the simulated visual environment. In this way, participants were able to observe the visual stimulus (i.e., radial, rotational or spiral flow) along the identical motion in depth.

In all experiments, the rotation direction was clockwise, and participants felt as though their bodies were rotating counterclockwise. We moved the cylinder from front to back in Experiment 1 and from back to front in Experiment 2; thus, participants felt as though they were moving forward in Experiment 1 and backward in Experiment 2.

2.3 Evaluation Methods of Vection Strength

We evaluated the vection strength using onset latency, duration, and vection strength rating. The onset latency was the time until the participants started experiencing self-motion, and a shorter onset latency indicated stronger vection. The duration was the sum of the time during which the participants experienced self-motion, where longer duration indicated stronger vection. The vection strength rating was a self-reported value of how strongly the participants felt they were moving.

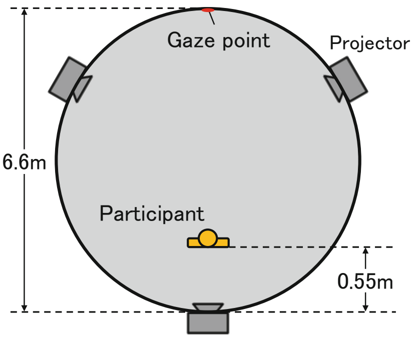


Fig. 2. Observation position of participant

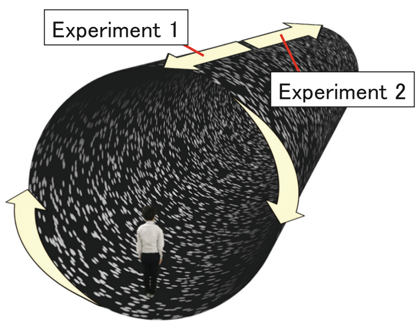


Fig. 3. Simulated visual environment

We used a Wii Remote controller to acquire the onset latency and duration. The controller was connected to the PC using the Bluetooth adapter, which transmitted data stably at 100 Hz. The participants kept the button of the Wii Remote depressed for the duration of the vection experience. The time at which the controller's button was first pressed was used for the onset latency, and the sum of how long the button was pressed was used for the duration. As soon as the visual stimulus presentation was finished, participants reported the vection strength using a 101-point rating scale ranging from 0 = "no vection" to 100 = "very strong vection".

3 Experiment 1

We investigated whether or not forward LV and counter-clockwise CV affect each other. In order to achieve this objective, the LV strength was acquired in Experiment 1a and the CV strength was acquired in Experiment 1b. If each vection did not affect the other, the acquired strength would be constant regardless of the other vection's strength. Each vection's strength was manipulated by changing the cylinder's velocity in each direction.

3.1 Experiment 1a

We acquired the LV strength by changing the radial and rotational velocity.

Experimental Condition
We manipulated the linear and rotational velocities of the visual stimulius. Each velocity factor possessed four levels. The prepared levels in the linear velocity factor were 0.0 m/s, 4.0 m/s, 8.0 m/s and 16 m/s and the prepared levels in the rotational velocity factor were 0.0°/s, 4.0°/s, 8.0°/s and 16°/s. Experiment 1a had twelve conditions combined with three linear velocities and four rotational velocities with the exception of 0.0 m/s.

Participants
Ten males and three females participated in this experiment, all of whom had normal or corrected-to-normal vision.

Experimental Procedure
The participants evaluated the LV strength while observing the spiral motion. The procedure for one trial is explained below.

There existed the possibility that participants neglected the circular motion due to excess concentration while evaluating LV. To avoid this possibility, the visual stimulus was presented with only rotational motion at the start of each trial. We waited to add linear motion until the participants indicated that they perceived CV by pressing the button. As soon as the button was pressed, we added the radial motion to the visual stimulus and presented a spiral motion. The participants were asked to keep the button depressed as long as the LV experience continued during the spiral motion's presentation. After observing of the spiral motion for 40 s, participants reported the vection strength using a 101-point rating scale.

The number of all trials was 36 per participant because we conducted three trials for each condition, and the order of trials was randomized for each participant.

Results

Figure 4 illustrates the onset latency for CV before the radial motion was added. A repeated-measures ANOVA revealed the significant main effects of the rotational velocity ($F_{(2,24)} = 19.654$, $p < 0.001$). A post hoc analysis using Bonferroni correction revealed significant differences illustrated in Fig. 4. Thus, CV was strengthened as the rotational velocity increased.

Figures 5, 6 and 7 illustrate the onset latency, duration, and strength for LV. For all indices, 3 (linear velocity) × 4 (rotational velocity) ANOVAs revealed the significant main effects of the linear velocity (onset latency $F_{(2,24)} = 33.529$, $p < 0.001$; duration: $F_{(2,24)} = 40.638$, $p < 0.001$, strength rating: $F_{(2,24)} = 98.484$, $p < 0.001$) and the rotational velocity (onset latency: $F_{(3,36)} = 7.251$, $p < 0.001$, duration: $F_{(3,36)} = 9.279$, $p < 0.001$, strength rating: $F_{(3,36)} = 5.469$, $p = 0.003$). The interaction was significant for the onset latency and duration (onset latency: $F_{(6,72)} = 6.521$, $p < 0.001$, duration: $F_{(6,72)} = 8.533$, $p < 0.001$); but insignificant for the strength rating ($F_{(6,72)} = 1.099$, $p = 0.372$). For the onset latency and duration, there was a significant, simple main effect of rotational velocity at 4.0 m/s (onset latency: $F_{(3,108)} = 19.459$, $p < 0.001$, duration: $F_{(3,108)} = 24.344$, $p < 0.001$). Post hoc analyses using Bonferroni correction

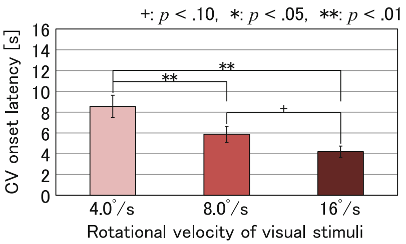


Fig. 4. CV onset latency before adding linear flow

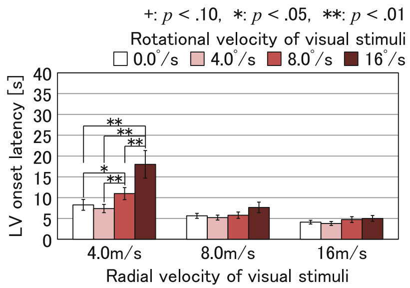


Fig. 5. LV onset latency after adding linear flow

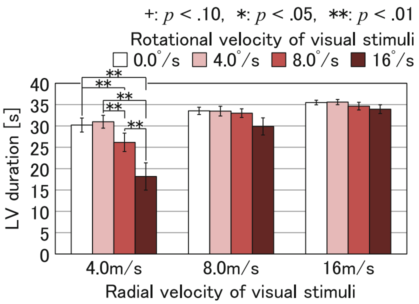


Fig. 6. LV duration after adding linear flow

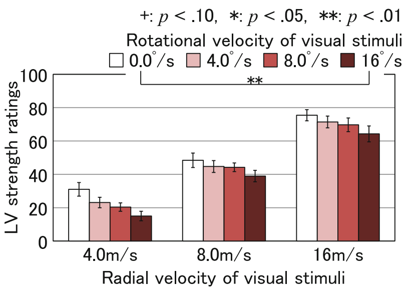


Fig. 7. LV strength ratings after adding linear flow

revealed significant differences shown in both Figs. 4 and 5. We found that LV was weakened as the rotational velocity of the visual stimulus became faster only when the radial velocity was slow.

In addition, a multiple comparison by Bonferroni correction was executed to investigate the effect of rotational velocity on the LV strength rating (Fig. 7). As a result, there was a significant difference between the 0.0°/s and the 16°/s condition ($p = 0.002$). This result indicates the LV strength decreased as the rotational velocity increased in the self-report following the observation; however, different from the onset latency and duration, the influence of linear velocity was constant under all linear velocity conditions.

3.2 Experiment 1b

We acquired the CV strength by changing the radial and rotational velocities.

Experimental Condition

Experiment 1b had twelve conditions combined four radial velocities (0.0 m/s, 4.0 m/s, 8.0 m/s and 16 m/s) and three rotational velocities (4.0°/s, 8.0°/s and 16°/s).

Participants

The same ten males and three females who participated in Experiment 1a also participated in Experiment 1b.

Experimental Procedure

With the exception of the presentation order of radial and circular motion, the procedure was identical to that used in Experiment 1a. The participants observed the visual stimulus with only the radial motion and pushed the button when they felt their bodies were moving (i.e., the LV onset latency). Next, we added circular motion to the visual stimulus and acquired the onset latency, duration, and strength for CV.

Results

Figure 8 illustrates the onset latency for LV before adding the circular motion to the visual stimulus. A repeated-measures ANOVA revealed the significant main effect of the radial velocity ($F_{(2,24)} = 22.490$, $p < 0.001$), and post hoc analyses revealed significant differences displayed in the Fig. 8. LV was strengthened as the radial velocity increased.

Figures 9, 10 and 11 illustrate the onset latency, duration, and strength rating for CV. For all indices, 4 (linear velocity) × 3 (rotational velocity) ANOVAs revealed the significant main effects of the radial velocity (onset latency: $F_{(3,36)} = 18.624$, $p < 0.001$, duration: $F_{(3,36)} = 30.948$, $p < 0.001$, strength rating: $F_{(3,36)} = 33.117$, $p < 0.001$) and the rotational velocity (onset latency: $F_{(2,24)} = 18.624$, $p < 0.001$, duration: $F_{(2,24)} = 90.274$, $p < 0.001$, strength rating: $F_{(2,24)} = 280.232$, $p < 0.001$), and the significant interaction (onset latency: $F_{(6,72)} = 10.391$, $p < 0.001$, duration: $F_{(6,72)} = 9.523$, $p < 0.001$, strength rating: $F_{(6,72)} = 3.520$, $p = 0.004$). In the onset latency and duration, significant, simple main effects of the radial velocity at 4.0°/s (onset latency: $F_{(3,108)} = 33.372$, $p < 0.001$, duration: $F_{(3,108)} = 40.860$, $p < 0.001$) and 8.0°/s (onset latency: $F_{(3,108)} = 9.752$, $p < 0.001$, duration: $F_{(3,108)} = 15.082$, $p < 0.001$). In the strength rating, significant, simple main effects of radial velocity at all levels of

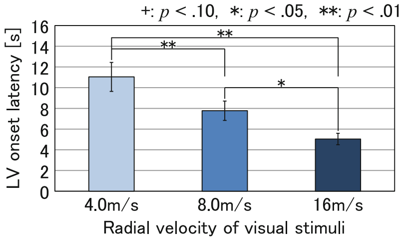


Fig. 8. LV onset latency before adding rotational flow

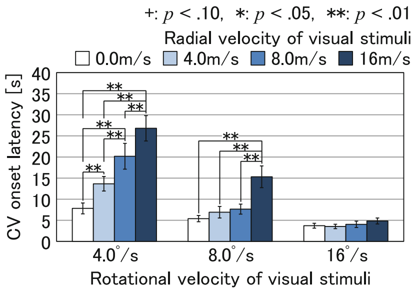


Fig. 9. CV onset latency after adding rotational flow

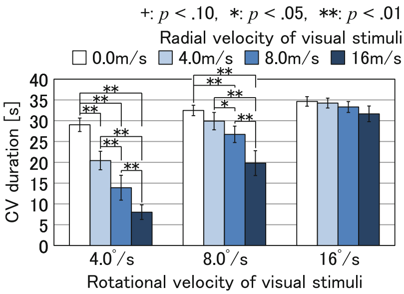


Fig. 10. CV duration after adding rotational flow

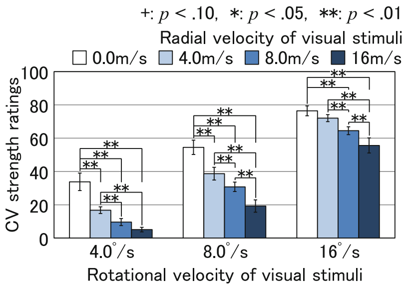


Fig. 11. CV strength ratings after adding rotational flow

rotational velocity (4.0°/s: $F_{(3,108)} = 22.186$, $p < 0.001$, 8.0°/s: $F_{(3,108)} = 30.649$, $p < 0.001$, 16°/s: $F_{(3,108)} = 11.626$, $p < 0.001$). Post hoc analyses using Bonferroni correction revealed significant differences that may be observed in Figs. 9, 10 and 11.

Discussion

The results of Experiment 1a demonstrate that the LV strength decreased as the rotational velocity increased; and, this influence of the rotational velocity on the LV strength was observed only when the radial velocity was slow. Considering that the CV strength increased as the rotational velocity increased, the visual stimulus of spiral motion producing stronger CV weakened the LV strength, which was perceived simultaneously. However, in some indices, such an effect of the CV strength disappeared when the participants observed the spiral motion with the faster radial velocity producing the stronger LV.

The results of Experiment 1b reveal the same tendency observed in Experiment 1a. As the radial velocity increased, the LV strength increased and the CV strength decreased. Therefore, it can be argued that the stronger the LV vection becomes, the weaker the CV strength becomes-an effect that decreases as the rotational velocity increases. From the results of Experiment 1, we found a negative correlation between the CV and LV strengths perceived from the spiral motion.

4 Experiment 2

To generalize the results of Experiment 1, we investigated whether backward LV and counter-clockwise CV affect each other. To achieve this objective, the LV and CV strengths were acquired in Experiments 2a and 2b.

4.1 Experiment 2a

We acquired the LV strength by changing the radial and rotational velocities.

Experimental Condition
We used the same twelve conditions used in Experiment 1a.

Participants
Ten males and two females different from those in Experiment 1 participated in Experiment 2a, all of whom had normal or corrected-to-normal vision.

Experimental Procedure
The experiment procedure was identical to that applied in Experiment 1a, with the exception of the radial movement's direction.

Results
Figure 12 illustrates the onset latency for CV before adding the radial motion to the visual stimulus. A repeated-measures ANOVA revealed the significant main effects of the rotational velocity ($F_{(2,22)} = 8.023$, $p = 0.002$), and a post hoc analysis using Bonferroni correction revealed significant differences that can be observed in Fig. 12. Stronger CV was produced from the visual stimulus with faster rotational velocity, and the onset latency and its trend were almost identical to those observed in Experiment 1a.

Figures 13, 14 and 15 show the onset latency, duration, and subject strength for LV. For all indices, 3 (linear velocity) × 4 (rotational velocity) ANOVAs revealed the significant main effects of the radial velocity (onset latency: $F_{(2,22)} = 24.115$, $p < 0.001$, duration: $F_{(2,22)} = 46.856$, $p < 0.001$, subject strength: $F_{(2,22)} = 37.077$, $p < 0.001$), the rotational velocity (onset latency: $F_{(3,33)} = 3.550$, $p = 0.025$, duration: $F_{(3,33)} = 7.643$, $p < 0.001$, subject strength: $F_{(3,33)} = 5.914$, $p = 0.002$), and the significant interactions (onset latency: $F_{(6,66)} = 4.508$, $p < 0.001$, duration: $F_{(6,66)} = 4.575$, $p < 0.001$, subject strength: $F_{(6,66)} = 2.720$, $p = 0.020$). For the onset latency, the significant, simple main effects of rotational velocity at 4.0 m/s ($F_{(3,99)} = 11.597$, $p < 0.001$); for the duration and subjective strength, the significant, simple main effects of the rotational velocity at 4.0 m/s (duration: $F_{(3,108)} = 14.720$, $p < 0.001$, subject strength: $F_{(3,108)} = 9.042$, $p < 0.001$) and 8.0 m/s (duration: $F_{(3,108)} = 3.351$, $p = 0.022$, subject strength: $F_{(3,108)} = 3.373$, $p = 0.022$). Post hoc analyses using Bonferroni correction revealed significant differences that can observed in Figs. 13, 14 and 15.

As with Experiment 1a, we found that LV was weakened when the visual stimulus's rotational velocity increased. Considering that the strength of CV increased as the rotational velocity increased, the CV strength perceived from the spiral motion increased and the LV strength perceived from the same motion decreased. Additionally, this effect disappeared when the linear velocity was fast.

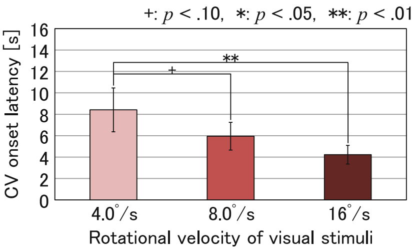


Fig. 12. CV onset latency before adding linear flow

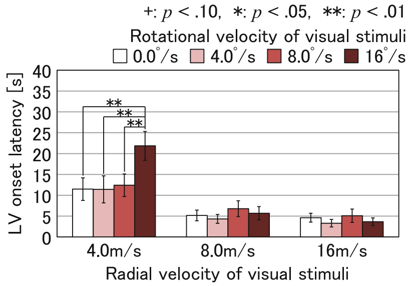


Fig. 13. LV onset latency after adding linear flow

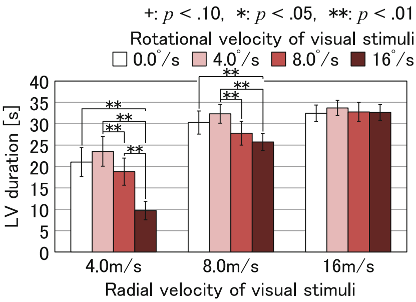


Fig. 14. LV duration after adding linear flow

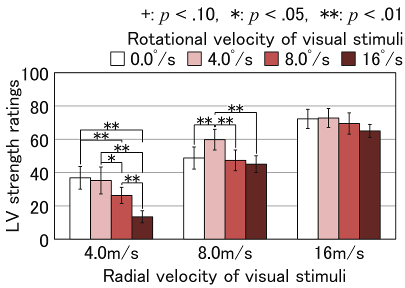


Fig. 15. LV strength ratings after adding linear flow

4.2 Experiment 2b

We acquired the CV strength by changing the radial and rotational velocities.

Experimental Condition
We adopted the same twelve conditions used in Experiment 1b.

Participants
The same ten males and two females who participated in Experiment 2a also participated in Experiment 2b.

Experimental Procedure
The experiment procedure was identical to that used in Experiment 1b, with the exception of the radial movement's direction.

Results
Figure 16 shows the onset latency for LV before adding the circular motion to the visual stimulus. A repeated-measures ANOVA revealed the significant main effect of linear velocity ($F_{(2,22)} = 6.995$, $p = 0.005$), and a multiple comparison using Bonferroni correction revealed the significant differences illustrated in Fig. 16. LV was strengthened as the radial velocity increased. Compared with the results of Experiment

1b (Fig. 8), the onset latency was slightly shorter. From this result, the backward LV was demonstrated to be perceived more easily than the forward LV.

Figures 17, 18 and 19 show the onset latency, duration, and strength rating for CV. For all indices, 4 (radial velocity) × 3 (rotational velocity) ANOVAs revealed the significant main effects of the radial velocity (onset latency: $F_{(3,33)} = 26.461$, $p < 0.001$, duration: $F_{(3,33)} = 47.215$, $p < 0.001$, strength rating: $F_{(3,33)} = 33.442$, $p < 0.001$), the rotational velocity (onset latency: $F_{(2,22)} = 50.183$, $p < 0.001$, duration: $F_{(2,22)} = 111.006$, $p < 0.001$, strength rating: $F_{(2,22)} = 93.366$, $p < 0.001$), and the significant interactions (onset latency: $F_{(6,66)} = 4.412$, $p < 0.001$, duration: $F_{(6,66)} = 6.068$, $p < 0.001$, strength rating: $F_{(6,66)} = 3.423$, $p = 0.005$). Significant, simple main effects of the radial velocity in all rotational velocities for the onset latency (4.0°/s: $F_{(3,99)} = 22.621$, $p < 0.001$, 8.0°/s: $F_{(3,99)} = 13.939$, $p < 0.001$, 16°/s: $F_{(3,99)} = 3.217$, $p = 0.026$), duration (4.0°/s: $F_{(3,99)} = 27.380$, $p < 0.001$, 8.0°/s: $F_{(3,99)} = 29.603$, $p < 0.001$, 16°/s: $F_{(3,99)} = 6.012$, $p < 0.001$), and strength rating (4.0°/s: $F_{(3,99)} = 12.108$, $p < 0.001$, 8.0°/s: $F_{(3,99)} = 24.768$, $p < 0.001$, 16°/s: $F_{(3,99)} = 18.944$, $p < 0.001$). Post hoc analyses using Bonferroni correction revealed the significant differences that can be observed in Figs. 17, 18 and 19.

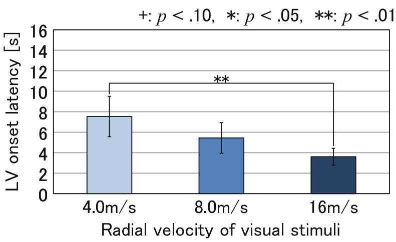


Fig. 16. LV onset latency before adding rotational flow

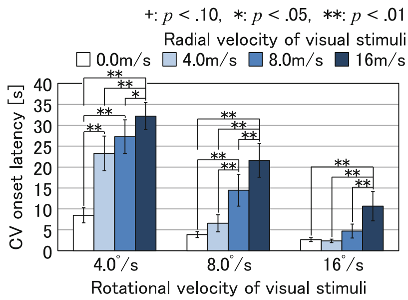


Fig. 17. CV onset latency after adding rotational flow

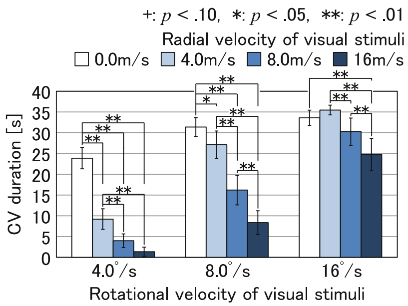


Fig. 18. CV duration after adding rotational flow

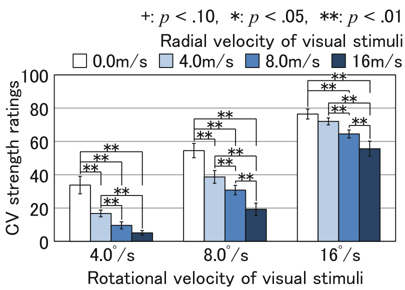


Fig. 19. CV strength ratings after adding rotational flow

As with Experiment 1b, we found that CV was weakened when the radial velocity of the visual stimulus increased. Considering that the strength of LV increased as the radial velocity increased, the LV strength perceived from the spiral motion increased, and the CV strength perceived from the same motion decreased. As illustrated in Figs. 17, 18 and 19, the differences between each radial velocity lessened as the rotational velocity increased; namely, the effect of radial velocity was more remarkable when the rotational velocity was slower.

Discussion
We confirmed the negative relation between CV and LV through Experiment 2. The results of both Experiments 2a and 2b reveal that increasing the velocity of one direction increase the strength of the corresponding vection and decreases the strength of the noncorresponding vection. However, when the velocity of one direction is fast, the influence from the other directiotn's velocity weakens or disappears.

5 General Discussion

We investigated the relationship between LV and CV perceived from the spiral motion based on the separately evaluated strength of each vection. The results of both Experiments 1a and 2a reveal that CV becomes stronger and LV becomes weaker as the rotational velocity of a visual stimulus increases. Similarly, the results of both Experiments 1b and 2b reveal that LV becomes stronger and CV becomes weaker as the radial velocity of a visual stimulus increases. These results suggest a negative relationship between CV and LV because CV weakened as LV strengthened and LV weakened as CV strengthed. In other words, LV and CV were not perceived or evaluated independently.

There are two possibilities as to why such a negative relationship was observed. The first possibility is the limitation of the cognitive resource. The faster motion draws more attention; therefore, observers tend to spend more cognitive resources processing it. As spared resource for another slower motion becomes small, and as a result, the faster motion prevents observers from experiencing the self-motion in another direction. The second possibility is that the observer cannot evaluate exactly how long the stimulus moves in each direction. Humans process stimuli holistically; therefore, it is difficult to extract a partial component (i.e., radial or circular only) from the spiral motion. As a result, humans simply provide a greater evaluation for the faster direction. We need further studies to investigate these possibilities.

Comparing the results of Experiments 1 and 2, there were some differences across the forward and backward LV. First, in the case wherein we added the radical motion to the circular motion (Experiments 1a and 2a), the backward LV was more susceptible to the circular motion. The rotational velocity affected the LV duration when the radial velocity was 8.0 m/s, which was not observed for the forward LV (Figs. 6 and 14). In addition, the onset latency was slower and the duration was shorter for the backward LV than were those for the forward LV, especially when the radial velocity was slow. On the other hand, when the rotational motion was added to the radial motion (Experiments 1b and 2b), the influence of the backward LV was stronger than that of the forward LV.

When the radial motion produced backward LV, the effect of the radial velocity was observed even if the rotational velocity was faster (Figs. 17 and 18), and the onset latency was shorter for backward LV than that for forward LV (Figs. 8 and 16).

The comparison of the two experiments' results reveals that backward LV is easily perceived and has stronger effects on CV than does forward LV. However, backward LV is susceptible to rotational velocity than is forward LV. One of possible reasons for this contradictory result is the frequency of everyday movements we experience. Generally, the opportunities to move forward are more frequent than those to move backward. We are accustomed to processing visual information for forward movement; therefore, we can easily neglect or pay attention to and then process such information. However, this is not the case for backward movement; we cannot adjust the sensitivity to visual information for backward movement. As a result, backward LV is susceptible to CV strength in some situations, while it is easily perceived and strongly influences CV strength in other situations.

6 Conclusion

From the results of our experiments, we determined there exists a negative correlation between the strengths of LV and CV. According to the visual stimulus wherein the strength of one vection was high, the strength of another vection became weak. Additionally, there were some differences in the effect of the forward and backward LV that imply what effect everyday observations of scenery produced by our movement have on the strength of perceived vection.

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