Analysis of Circular Vection Deriving from Mutual Effect between Rotational and Linear Visual Stimuli

Yuma Koga*/College of Information Science and Engineering, Ritsumeikan University, Akihiro Konishi/ Graduate School of Information Science and Engineering, Ritsumeikan University, Satoshi Hashiguchi, Asako Kimura, Fumihisa Shibata/ College of Information Science and Engineering, Ritsumeikan University, and Hideyuki Tamura/ Research Organization of Science and Technology, Ritsumeikan University

* *koga@rm.is.ritsumei.ac.jp*

Abstract: Vection is a self-motion illusion caused by observing a moving pattern in a certain direction (called "visual stimulus"). There are two types of vection depending on the movement direction: linear vection (LV, i.e. rectilinear motion sense) and circular vection (CV, i.e. rotational motion sense). Previous studies analyzed LV and CV separately; however, few studies have investigated the mutual effects between LV and CV. This study, as the first step toward analyzing the mutual effects between LV and CV, focuses on and examines the relationship between the rectilinear movement speed of the visual stimulus and the CV strength. We found that the CV strength increased when the rectilinear movement speed decreased.

Keywords: vection, linear vection, circular vection, self-motion, immersive display

1. Introduction

When a visual stimulus moves uniformly in one direction, an observer perceives an illusion of self-motion in the opposite 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 moving in the opposite direction. In other words, the observer perceives forward motion by observing a moving pattern in the backward direction. This phenomenon is called vection, and the self-motion illusion direction is perceived to be opposite to the pattern movement direction.

The observer can also perceive rotational motion depending on the type of visual stimulus observed. The perceived direction of rotation is opposite to that of the visual stimulus, as in the case of rectilinear motion. Therefore, depending on the movement direction, there are two types of vection: linear vection (LV), or rectilinear motion sense, and circular vection (CV), or rotational motion sense [1].

Vection can be used to express and reproduce rectilinear and rotational motion sense without actually moving. The strength of self-motion sensation (vection strength) caused by observing the visual stimulus is used as the index of immersion in a virtual reality (VR) environment [2]. Expression and immersion in VR space can be improved by analyzing the occurrence trend of vection and elucidating its mechanism.

In VR content, LV and CV are sometimes used separately, as analyzed in some studies. They are often also used in combination; however, few studies have focused on their mutual effects. We study the simultaneous perception of LV and CV by using visual stimuli moving in linear and circular directions. We also determine the CV strength as the first step toward analyzing the mutual effects of LV and CV.

Many studies have previously focused on CV. Brandt et al. [3] showed that CV became stronger as the rotational speed of visual stimuli increased; they also showed that the increase in CV strength decreases as the rotational speed of visual stimuli increases. Some studies focused on the relationship between vection and field-of-view, and others studied the provided area of visual stimuli [4] [5]. These studies showed that vection was stronger when the provided area of the visual stimulus in peripheral vision became wider. Thus, when studying vection, visual stimulus must be provided to a sufficiently wide field-of-view. For this purpose, we used a wide-field-of-view display system.

2. Experimental setup

2.1. Wide-field-of-view display system

In this study, we constructed an immersive display system to present a visual stimulus to a person's entire field-of-view. We used a dome-shaped screen with 7.0-m diameter and 3.8-m height that can display a full 360° scene using three projectors on the inside of the dome, as shown on Figure 1.

The projector light may dazzle subjects' eyes and cast their shadows on the screen, because our display system uses front projection. To deal with these issues, we set black color on subjects' head positions by using the projector, and we decided their positions such that their shadows did not appear on the screen [6]. Black color means that the projector light is absent; thus, subjects do not mind the direction of the projector light and their own shadow.

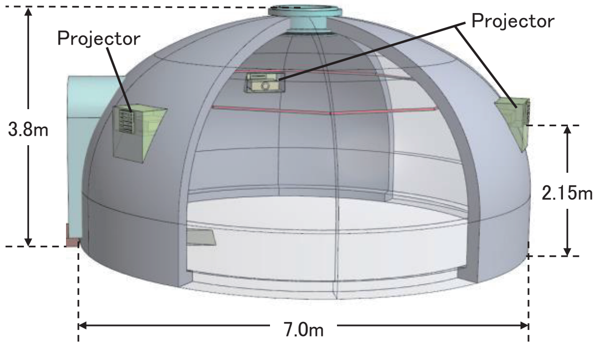


Figure 1: Wide-field-of-view display system and position of each projector.

2.2. Visual stimulus

As in previous studies [7], we used a VR space to generate a seamless uniform visual stimulus. We used a 6.0-m-diameter virtual cylinder on which a texture image was displayed. We generated a visual stimulus as a 360° scene by rendering this virtual cylinder from inside, and we projected an image on the inside wall of the immersive display screen in real-time. We can obtain visual stimuli moving in rectilinear and rotational directions by translating and turning the cylinder, respectively. We set the rectilinear and rotational directions to the rear and clockwise directions, respectively.

The texture image with random dots was displayed on the virtual cylinder so that subjects can perceive LV and CV clearly. The size of dot (diameter) was set so the visual angle of the dot placed right beside the subject was 2°. The density of white dots, that is, black-to-white ratio, was approximately 4:1. The vanishing point of the visual stimulus was set as subjects' eye height (1.6 m), and the red gaze point was set to the same height to fix subjects' eye directions. Figure 2 shows one frame of the stimulus.

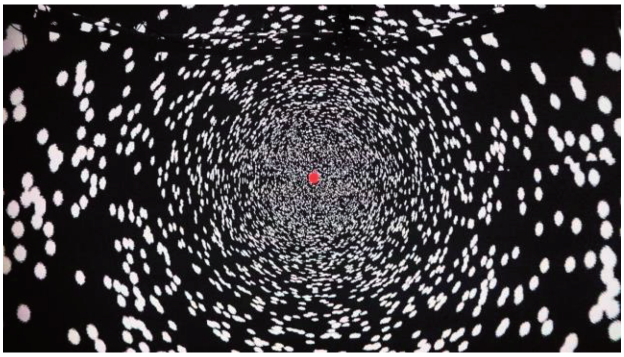


Figure 2: Visual stimuli projected onto dome wall.

Table 1: Evaluation value of five stages.

Evaluation value	Meaning of value
-2	The former is clearly stronger
-1	The former is slightly stronger
0	Both have same strength
1	The latter is slightly stronger
2	The latter is clearly stronger

2.3. Experimental method and condition

We used Scheffé's paired comparison method (Ura's variation) to evaluate the vection strength. Subjects observed two visual stimuli, and then, they answered questions about which pattern showed stronger vection in five stages, as shown in Table 1. Accordingly, we could easily create a psychological measure with an interval scale. The difference between adjacent pairs of scale values indicates the psychological difference that the subject feels from these two stimuli. Thus, we can analyze or estimate the psychological difference between stimuli from the interval of the values plotted on the number line.

We analyze the vection caused by observing the rotational visual stimuli with linear movement. To compare vection strengths, the subject needs to understand the vection strength with each visual stimulus. Therefore, the visual stimulus was presented until the subject perceived the vection strength. We presented linear and rotational motions step-by-step so that the subject could understand both LV and CV strengths. In a preliminary experiment to focus on LV (Section 3), we presented rotational visual stimuli until the subject perceived the CV and then we added linear movement. In experiments 1 and 2 to focus on CV (Sections 4 and 5 respectively), we presented visual stimuli of linear motion until the subject perceived LV then added rotational movement.

3. Preliminary experiment: Confirmation of relationship between linear velocity of visual stimulus and LV strength

3.1. Experimental objective

Vection strength is influenced by various factors such as the direction or velocity of visual stimuli. Brandt *et al.* [3] showed that CV became stronger when the rotational speed (angular velocity) of visual stimuli increased. Shimamura *et al.* [8] showed that LV velocity increased when the linear velocity of visual stimuli increased. As shown above, both LV and CV are affected by the speed of visual stimuli.

Visual stimuli have two types of speed: linear speed (i.e., linear velocity) and circular speed (i.e., rotational velocity). The speeds in each direction, namely, linear velocity and circular velocity, can affect the LV and CV strength independently.

Through a preliminary experiment, we verify whether the linear velocity affects the LV strength when the visual stimuli move in linear and circular directions.

3.2. Experimental condition

The subject stood 0.55 m from the dome wall, and random dots (Section 2.2) were presented as the visual stimulus (Figure 3). The linear and rotational velocities were set as

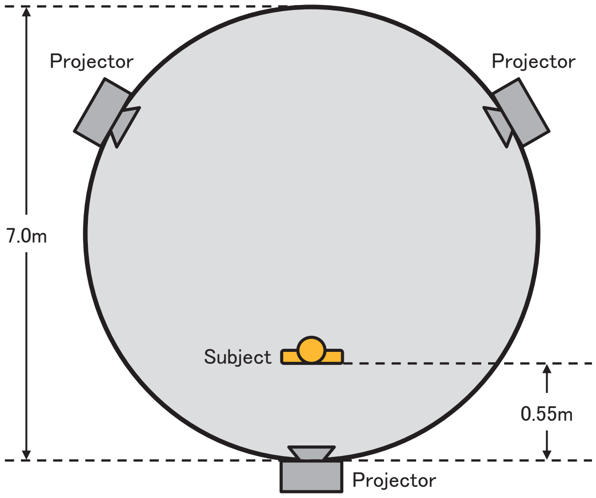


Figure 3: Observation position of subject.

Table 2: Velocity of visual stimuli
in preliminary experiment.

Angular velocity	Linear velocity
10°/s	4.0 m/s
	8.0 m/s
	12 m/s

shown in Table 2. The number of experimental patterns was 3. A total of 12 adults (10 males and 2 females) participated in the study.

3.3. Experimental procedure

The experiment was based on Scheffé's method, as noted in Section 2.3. We counted trials in which the presentation order is changed as another trial; thus, the number of attempts was ${}_3C_2 \times 2 = 6$ times per subject. We conducted a sufficient number of practice trials beforehand so that subjects could compare the LV strength.

The experimental procedure is as follows:

(1) Two patterns were randomly selected from Table 2
(2) One of the two patterns was presented to the subject
(3) The other pattern was presented to the subject
(4) The subject was asked which pattern showed stronger vection (LV) in five steps after trying both a first and a second time
(5) To eliminate the effects of fatigue, enough time was given for the subjects to rest
(6) Steps (1)–(5) were repeated for the remaining combinations

We performed the trial again after a 1-min break if the subject wanted to do so in Step (4), and we prepared an additional break (at least 3 min) separately from step (5) once every four trials in the experiment.

3.4. Results

Figure 4 shows the experimental results. The number line represents the psychological scale of the strength of each visual stimulus. The subject feels stronger LV when the numerical value is larger. The figure shows that LV was stronger when the linear velocity of the visual stimuli was high. The ANOVA results were significant ($p < 0.01$). We used Scheffé's method as a post-hoc hypothesis test; there are significant differences between all pairs of visual stimuli conditions, as shown in Figure 4. This also indicates that the subject clearly understands the differences in LV strength at each linear velocity.

These results indicate that the linear velocity affects the LV strength when the visual stimuli move in linear and circular directions.

4. Experiment 1: Analysis of relationship between linear velocity of visual stimulus and CV strength

4.1. Experimental objective

The preliminary experiment showed that LV became stronger when the linear velocity of the visual stimuli was high as they moved in linear and circular directions. We conducted experiment 1 to confirm whether the linear velocity affects the CV strength when using the same visual stimuli as in the preliminary experiment.

4.2. Experimental condition

As in the preliminary experiment, the subject stood 0.55 m from the dome wall, and the visual stimulus was presented (Figure 3). The linear velocity was set as 0.0 m/s, that is, the visual stimuli move in only the circular direction. The number of experimental patterns was 4 (Table 3).

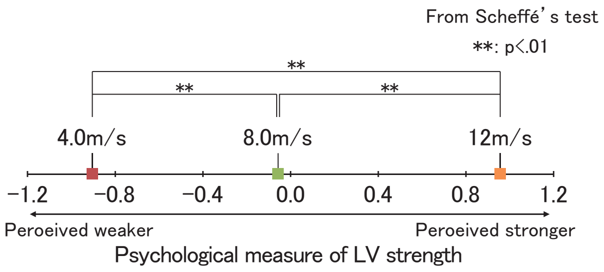


Figure 4: Relationship between LV strength and linear velocity of visual stimuli.

Table 3: Velocity of visual stimuli in experiment 1.

Angular velocity	Linear velocity
10°/s	0.0 m/s (no linear motion)
	4.0 m/s
	8.0 m/s
	12 m/s

The subjects were the same as before.

4.3. Experimental procedure

The experiment was based on Scheffé's method, as noted in Section 2.3. The same calculation method as in the preliminary experiment was used; therefore, the number of attempts was ${}_4C_2 \times 2 = 12$ times per subject. We conducted a sufficient number of practice trials beforehand so that subjects could compare the CV strength.

The experimental procedure is as follows:

(1) Two patterns were randomly selected from Table 3
(2) One of the two patterns was presented to the subject
(3) The other pattern was presented to the subject
(4) The subject was asked which pattern showed stronger vection (CV) in five steps after trying both a first and a second time
(5) To eliminate the effects of fatigue, enough time was given for the subjects to rest
(6) Steps (1)–(5) were repeated for the remaining combinations

We performed the trial again after a 1-min break if the subject wanted to do so in Step (4), and we prepared an additional break (at least 3 min) separately from step (5) once every four trials in the experiment.

4.4. Results and discussion

Figure 5 shows the experimental results. The number line represents the psychological scale of the strength of each visual stimulus. The subject feels stronger CV when the numerical value is larger. The ANOVA results were significant ($p < 0.01$). We used Scheffé's method as a post-hoc hypothesis test; there are significant differences between all pairs of visual stimuli conditions, as shown in Figure 5.

The figure shows the following:

(i) CV became stronger when the linear velocity of the visual stimuli was low.
(ii) The interval between values plotted on the number line increased when the linear velocity of the visual stimuli was low.

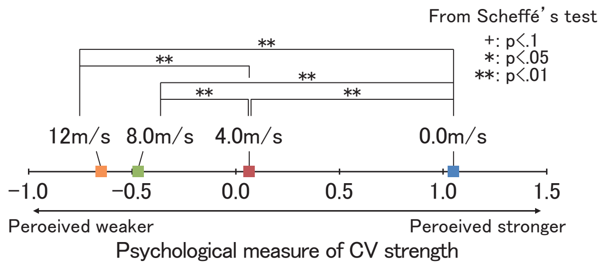


Figure 5: Relationship between CV strength and linear velocity of visual stimuli.

Before experiment 1, we thought that linear and angular velocities affect only LV and CV, respectively, because the vection and velocity of the visual stimuli can be separated into two directions. However, unexpectedly, the results showed that the linear velocity could affect the CV strength if the visual stimuli move in linear and circular directions.

Result (i) and the preliminary experiment suggest that CV becomes stronger when LV becomes weaker if the visual stimuli move in linear and circular directions. This means that the LV strength affects the CV strength, and the LV and CV strengths show negative correlation if perceived simultaneously. Furthermore, CV was the strongest when the linear velocity of the visual stimuli was 0.0 m/s, and there were significant differences between 0.0 m/s and all other linear velocities of the visual stimuli. This result supports the above consideration. In addition, result (ii) indicates that the subject clearly understood the differences in CV strength at each linear velocity when the linear velocity of the visual stimuli was low. Remarkably, there is no contradiction between the above hypothesis and this result.

Experiment 1 confirmed that the linear velocity affects the CV strength when using the same visual stimuli as in the preliminary experiment and that CV became stronger when the linear velocity of the visual stimuli was low. This suggests that the LV and CV strengths show negative correlation when perceived simultaneously.

5. Experiment 2: Analysis of relationship between linear velocity of visual stimulus and CV strength at other angular velocities

5.1. Experimental objective

The results of experiment 1 were confirmed only at an angular velocity of 10°/s for the visual stimuli. Results need to be obtained at other angular velocities of the visual stimuli for further discussion. We conducted experiment 2, which was similar to experiment 1, with other angular velocities of the visual stimuli to confirm whether the linear velocity of the visual stimuli affects the CV strength.

5.2. Experimental condition and procedure

The subject's observation position and the linear velocity of the visual stimuli were the same as in experiment 1. However, the angular velocities of the visual stimuli were set to 5.0°/s, 20°/s, and 30°/s. Furthermore, we did not compare the CV strength under different angular velocities of the visual stimuli. The number of experimental patterns was 5 (Table 4 (a), (b), and (c)).

Table 4: Combination of linear and angular velocity of visual stimuli in experiment 2.

(a) Angular velocity = 5.0°/s

angular velocity	Linear velocity
5.0°/s	0.0 m/s (no linear motion)
	4.0 m/s
	8.0 m/s
	12 m/s

(b) Angular velocity = 20°/s

Angular velocity	Linear velocity
20°/s	0.0 m/s (no linear motion)
	4.0 m/s
	8.0 m/s
	12 m/s

(c) Angular velocity = 30°/s

Angular velocity	Linear velocity
30°/s	0.0 m/s (no linear motion)
	4.0 m/s
	8.0 m/s
	12 m/s

To eliminate the effects of fatigue, this experiment was conducted on a different day from experiment 1. Furthermore, the experiment for each angular velocity was conducted on a different day. Therefore, experiment 2 was conducted over three days for each subject. The subjects were the same as before.

The experimental procedure was the same as in experiment 1.

5.3. Results and discussion

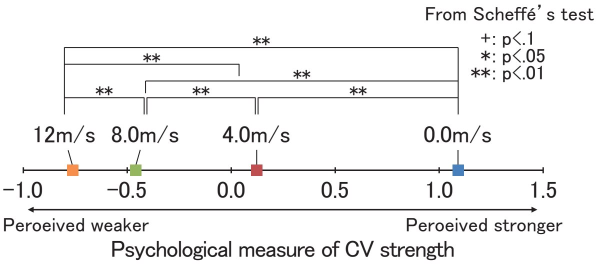
Figure 6 (a), (b), and (c) show the experimental results for each angular velocity of the visual stimuli. The ANOVA results were significant ($p < 0.01$) at all angular velocities. We used Scheffé's method as a post-hoc hypothesis test; there are significant differences between all pairs of visual stimuli conditions, as shown in Figure 6 (a), (b), and (c).

The figure shows the following:

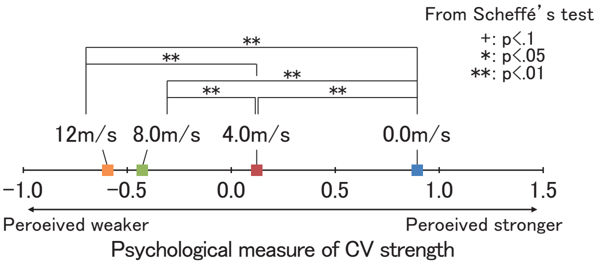
(i) CV became stronger when the linear velocity of the visual stimuli was low for all angular velocities of the visual stimuli.
(ii) The interval between values plotted on the number line increased when the linear velocity of the visual stimuli was low for all angular velocities of the visual stimuli.
(iii) Significant differences between any pair of visual stimuli conditions increased when the angular velocity of the visual stimuli was low.

Results (i) and (ii) are similar to those in experiment 1 in which the angular velocity of the visual stimuli was set to 10°/s. The linear velocity also affects the CV strength at other angular velocities of the visual stimuli. This suggests that CV becomes stronger when LV becomes weaker, that is, the LV and CV strengths show a negative correlation, when the visual stimuli moves in linear and circular directions.

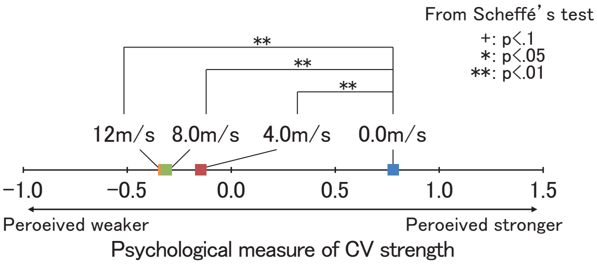
Result (iii) indicates that the subject clearly understood the differences in CV strength when the angular velocity of



(a) Angular velocity = 5.0°/s



(b) Angular velocity = 20°/s



(c) Angular velocity = 30°/s

Figure 6: Relationship between CV strength and linear/angular velocity of visual stimuli.

the visual stimuli was low. Now, for the pair of 12 and 8.0 m/s, there were no significant differences when the angular velocity of the visual stimuli was set to 20°/s; however, there were significant differences when it was set to 5.0°/s. This means that the influence of the linear velocity of the visual stimuli on the CV strength increases when the angular velocity of the visual stimuli is low. Result (iii) and the preliminary experiment suggest that the influence of the LV strength on the CV strength increases when the angular velocity of the visual stimuli is low.

Experiment 2 confirmed that the linear velocity of the visual stimuli affects the CV strength regardless of the angular velocity of the visual stimuli. Furthermore, the influence of the linear velocity of the visual stimuli on the CV strength increases when the angular velocity of the visual stimuli is low. Thus, the CV strength is affected by the visual stimuli moving in both the linear and circular directions. This suggests that the influence of the LV strength on the CV strength increases when the angular velocity of the visual stimuli is low. Therefore, these findings are useful for designing VR contents which simultaneously present linear and rotational motions.

6. Conclusions

Previous studies analyzed LV and CV separately; however, few studies analyzed the mutual effects between LV and CV. This study focuses on the relationship between the linear velocity of visual stimuli and the CV strength as the first step toward analyzing the mutual effects between LV and CV.

In a preliminary experiment, we found that LV became stronger when the linear velocity of the visual stimuli was high if the visual stimuli move in linear and circular directions. This means that the linear velocity affects the LV strength when we perceive LV and CV simultaneously.

Experiment 1 showed that CV became stronger when the linear velocity of the visual stimuli was high under the same conditions as in the preliminary experiment. This shows that the linear velocity also affects the CV strength. The preliminary experiment and experiment 1 suggested that CV became stronger when LV became weaker. In other words, the LV and CV strengths showed negative correlation when perceived simultaneously.

Experiment 2 showed that the linear velocity of the visual stimuli affects the CV strength at all angular velocities of the visual stimuli. This suggested that the LV and CV strengths showed negative correlation when perceived simultaneously at all angular velocities of the visual stimuli. The subjects clearly understood the differences in CV strength at each linear velocity when the linear velocity of the visual stimuli was low. This indicated that the negative correlation of the LV and CV strengths would appear clearly when the angular velocity of the visual stimuli was low.

We focused on and examined the relationship between the linear velocity of the visual stimuli and the CV strength. We also need to examine the relationship between the angular velocity of the visual stimuli and the LV strength to analyze the mutual effects between LV and CV. We will focus on and examine this issue in the future.

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