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Jiang, Moyou
Graduate School of Design, Kyushu University

Guo, Xuanru
Graduate School of Design, Kyushu University

Seno, Takeharu
Faculty of Design, Kyushu University

Remijn, Gerard B.
Faculty of Design, Kyushu University

他

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KYUSHU UNIVERSITY

Moyou Jiang*
Xuanru Guo*
Graduate School of Design
Kyushu University
Minami-ku, Fukuoka, 815-8540
Japan

Takeharu Seno*
Gerard B. Remijn
Faculty of Design
Kyushu University
Minami-ku, Fukuoka, 815-8540
Japan

Shinji Nakamura
Faculty of Education and Psychology
Nihon Fukushi University
Okuda, Mihama-cho, Chita-gun,
Aichi, 470-3295
Japan

Examination of the Effect of the Real-Life Meaning of the Stimulus on the Self-Motion Illusion

Abstract

Vection refers to the illusory self-motion perception mainly induced by the motion of a visual stimulus. This phenomenon concerns presence and immersion in the illusion of self-motion, especially in virtual reality. In the present study, we investigated how the real-life meaning of stimuli contributes to vection by using animations of objects that can move by themselves. In two psychophysical experiments, we first employed animated cars presented with or without wheel rotation as the visual inducer, using various motion directions and postures; then we added the road scenery, which was either moving (in the same or opposite direction to the cars) or still, as a contextual background in the visual stimulus. The results of Experiment 1 showed that in conditions with forward- and backward-moving cars, vection was stronger than in conditions with upward-moving and inverted cars. The results of Experiment 2 showed that vection was weakest in the still road scenery condition and that the cars' wheel rotation could facilitate vection. This suggests that the more natural the stimulus meanings, the stronger the vection. It is a feasible and effective application prospect to enhance the vection experience by changing the naturalness of the stimulus to further increase the sense of presence and immersion. Therefore, the perceived naturalness and the assumed immobility of the visual inducer are two important cognitive factors in visual self-motion perception and presence in the virtual world.

1 Introduction

Vection is the general term for a visually induced, illusory self-motion perception. Generally, physically stationary observers often perceive themselves as moving if they perceive their surrounding environment, which should have been still, as moving. Vection is now often used for various purposes in VR environments, amusement parks, and also in animation and movies (Kruijff et al., 2016). Specifically, when observers are exposed to a uniformly moving visual stimulus that occupies a large part of their visual field, they typically perceive illusory motion of their self-body in the direction opposite to the visual inducer's motion. Vection can occur, for example, when we observe moving clouds or streaming water (Dichgans & Brandt, 1978; Palmisano, Allison, Kim, & Bonato, 2011; Palmisano, Allison, Schira, & Barry, 2015). At present, previous studies usually used subjective report or measurement methods to measure vection intensity, such as latency, duration, subjective strength, and distance

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*Correspondence to jiangmoyoudufl@163.com, guoxuanru1101@gmail.com, seno@design.kyushu-u.ac.jp.

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travelled; more objective methods are also under further development (Kooijman et al., 2024).

This phenomenon involves the dynamic interplay between presence and immersion, particularly in simulating self-motion within virtual reality (VR). Immersion, defined by the extent of user engagement and absorption in a virtual environment, includes sensory elements like visual, auditory, and sometimes haptic feedback (Servotte et al., 2020). Presence, in contrast, represents the subjective feeling of truly existing within the virtual world, emphasizing a sense of "being there" (Han et al., 2022). The past research has extensively studied the positive correlation between vection and presence, and vection and immersion.

For instance, experiments simulating forward self-motion using the Oculus Rift head-mounted display showed participants with different sequential yaw head movements consistently demonstrating parallel trends in both vection and presence. This positive relationship persisted across a broad range of head-to-display lags (Kim et al., 2022). Similar findings emerged in studies involving spatial presence, where various optical flow stimuli observed through a head-mounted display in a virtual environment produced analogous results. Additionally, research revealed that anisometropia suppression concurrently diminished both vection intensity and spatial presence (Luu et al., 2021). Notably, this positive relationship endured even in the presence of visual-induced motion sickness, commonly referred to as cybersickness (Kooijman et al., 2022b).

Furthermore, some studies have integrated virtual reality technology to construct immersive environments, demonstrating that the strength of vection is heightened in scenarios mimicking immersion in water (Fauville et al., 2021). Additionally, immersive environments are widely used in movie stages and other contexts. For example, researchers have found through the movie ride effect that there is a direct connection between vection and immersion (Najm, 2019). In virtual environments, there is a positive correlation between immersion and presence (Servotte et al., 2020). This synthesis of research findings underscores the intricate dynamics between vection, presence, and immersion within virtual reality contexts. Studying the relationship between vection, presence, and immersion holds significant importance and application prospects for the future existence and experience of virtual worlds.

Vection is typically a subjective illusory experience triggered by visual grating motion stimuli presented in a 2D display environment. Previous research has demonstrated that vection experiences can also be induced by auditory and tactile stimuli (Väljamäe, 2009; Kooijman et al., 2022a). If the stimulus can be presented in different modalities and rendered more realistically and immersed for an extended period, such as through virtual reality (VR) (Xiong et al., 2021), would there be no difference between the vection illusion experience and our real movement? In this case, it may feel the same as actual self-movement, leading to the loss of the illusion of moving while actually moving. This nuanced perspective challenges our understanding of vection as a typical self-motion illusion, suggesting it can be perceived as actual movement within the metaverse space. This realization underlines the interconnectedness of vection, presence, and immersion in the virtual world, reinforcing the study's focus on exploring factors, including naturalness, to enhance the overall immersive experience and comfort in virtual reality. Previous research has explored the impact on vection intensity from two perspectives: top-down and bottom-up. However, naturalness, an important factor that affects vection intensity and the sense of presence in the virtual world, remains to be further explored. By creating different new visual stimuli and by varying the naturalness level of these stimuli on vection intensity, more immersion and presence and virtual world experiences can be created.

2 Literature Review

Many researchers have examined visual factors that are effective in vection induction, and they have found several important facts which are valuable in understanding the perceptual and neural processes underlying self-motion. Vection types are usually divided into linear and circular vection and other types based on different stimulus types, with most studies examining linear vection. For example, it is well known that the visual field in

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which the visual inducer is presented can have a strong impact on linear vection: a visual stimulus presented in the observer's peripheral visual field can be more effective in inducing vection than one presented in the central visual field (Brandt et al., 1973; Johansson, 1977; Dichgans & Brandt, 1978; Howard & Heckmann, 1989; however, see Nakamura & Shimojo, 1998; Andersen & Braunstein, 1985; Howard & Heckmann, 1989; Nakamura, 2001, 2008; Post, 1988; Wolpert, 1990, for contrary findings). Other stimulus factors which can affect the occurrence and strength of linear vection are, amongst others, stimulus size (e.g., Brandt et al., 1973; Nakamura & Shimojo, 1998; Allison et al., 1999), motion speed (e.g., Brandt et al., 1973; Allison et al., 1999; Fujii et al., 2019; Andersen & Braunstein, 1985), stimulus depth structure (e.g., Andersen, & Braunstein, 1985; Brandt et al., 1975; Nakamura, 2006; Howard & Heckmann, 1989), and additional accelerating motion (e.g., Palmisano, Allison, & Pekin, 2008; Palmisano, Allison, et al., 2014).

In addition to these stimulus factors, several studies have also indicated that vection is sensitive to the cognitive state of the observers (e.g., Riecke, Schulte-Pelkum, et al., 2006; Riecke & Schulte-Pelkum, 2013; Riecke, 2009). In particular, vection strength can be affected by experimental instructions. For example, Palmisano and Chan (2004) showed that linear vection strength became weaker when the experimental instructions biased the participants toward the perception of object-motion, rather than self-motion. Furthermore, based on the cognitive/perceptual frameworks of movability proposed by Riecke (2009), prior knowledge indicating the possibility of actual movement by the observer had an impact on vection perception. Specifically, Lepecq et al. (1995) reported that when participants (7- and 11-year-old children) were informed before actual experiments that their seat was able to move in correspondence with the visual stimulation (backward linear vection stimuli), vection latency could be shortened, that is, occurred with a faster onset. Their findings thus indicated that cognitive information about actual movement could facilitate self-motion perception (also see Wright et al., 2006, for cognitive contribution to oscillatory linear vection in adults, though Schulte-Pelkum (2008) and Schulte-Pelkum et al. (2004) failed to find any cognitive contribution to circular vection in adults). In addition, some studies reported that the use of a restraining shoulder harness, which tied participants to the stationary floor, would reduce the strength of roll vection (Young et al., 1983; Young & Shelhamer, 1990). Their findings thus indicated that vection could be affected both in a cognitive way (e.g., prior knowledge about movability of the observer themselves) and a perceptual way (e.g., the tactile sensation). Similarly, Riecke, Feuereissen, et al. (2008, 2009) reported the combinational contribution of both cognitive and perceptual factors in auditory circular vection. Together, these previous studies thus have suggested that vection is a perceptual phenomenon which is not only determined by the physical characteristics of the vection stimulus, but also by cognitive factors.

Cognitive factors in vection have also been studied in another way. Ogawa and Seno (2014) reported that assumed linear vection strength was modulated by the interpretation of the "real-life meaning" of the vection stimulus in the physical world. They reported that vection strength was reduced in conditions where the vection inducer was composed of visual objects that could move in the environment, independent of the observer's self-motion. Real-life or animated real-life objects, such as downward-moving feathers, petals, and leaves, induced less pronounced vection as compared to stimuli with no specific real-life meaning (e.g., random dots, which are commonly used in vection experiments), even though the motions of the visual stimuli in both conditions were completely identical. The reason why the downward motion of "natural" visual objects caused less strong self-motion is that the motion can be interpreted as "object-motion," caused by the earth's gravity, and not as a consequence of the observer's self-motion. This motion processing involved motion parsing. This is a perceptual process in which the visual system segregates different sources of motion information within a scene. Essentially, it involves the ability to distinguish between self-generated motion and motion generated by external sources. The human visual system is adept at parsing or separating these various motion cues to create a coherent understanding of the visual environment. In the context of visual perception, motion parsing helps

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individuals attribute movements to specific objects or entities in a scene. While you are walking through a park, your visual system parses the motion of trees, benches, and other static objects as being caused by your own movement. Simultaneously, it distinguishes the motion of other people, animals, or vehicles moving independently within the scene (Field et al., 2020; Warren, & Rushton, 2007).

The results of Ogawa and Seno (2014) are consistent with the idea that vection is based on a perceptual process which attributes retinal image motion of the visual stimulus to the observer's self-motion—not to object-motion in the external world (Dichgans & Brandt, 1978; Palmisano et al., 2015). In the former case, the retinal image motion of the visual stimulus would be interpreted as the apparent motion of externally static objects caused by the observer's self-motion. Other studies also reported similar effects for auditory stimuli. For example, sound sources that are associated with stationary objects (so-called auditory landmarks, like church bells or a fountain) are more instrumental in inducing auditory vection than artificial sounds (e.g., pink noise) and sounds originating from moving objects, like the sound of footsteps or a driving car (Larsson et al., 2004; Riecke et al., 2005; Väljamäe et al., 2009). Following this, in the current investigation, we hypothesized that visual stimuli which are assumed to be static and not moving in the real world can induce stronger vection than stimuli that would be able to move in real life, independent from the observer. We refer to this notion as the "mobile/static hypothesis" of vection.

Cognitive factors in vection are not solely affected by stimulus movability (whether referring to the physically (im)movable observer themselves or vection-inducing stimuli), but can also be manipulated by stimulus naturalness. Previous studies have revealed that more natural visual stimuli, often observed in daily life, can induce stronger self-motion perception (e.g., Bubka & Bonato, 2010; Kim et al., 2016; Riecke et al., 2006; Riecke, Västfjäll, Larsson, & Schulte-Pelkum, 2005). Specifically, Riecke et al. (2006) examined vection induced by video footage of movement through a city scene and compared vection strength between conditions with a normal upright (natural) scene and an upside-down (unnatural) scene. Although both conditions shared similar physical stimulus properties, the resulting self-motion was much stronger in the former than in the latter condition. Thus, we can assume that a more natural visual stimulus can induce vection more effectively than a less natural stimulus. The vection-facilitating effect of the naturalness of the visual stimulus might be caused by the fact that perceptual processing is less effortful for more familiar visual stimuli (Bubka et al., 2008). We refer to this as the "naturalness hypothesis" for vection (Nakamura, 2013).

As mentioned above, the cognitive meaning of the visual stimulus possibly affects vection via two possible ways, namely its movability/staticity in the external world and its naturalness. The main motivation of the present investigation is to address the relative contributions of these two factors to vection. In two experiments reported in this paper, we employed objects that could spontaneously move by means of an energy source in the external world, that is, moving cars (schematically drawn as simple cartoons), as visual stimuli. In Experiment 1, we varied two factors in these animations, namely the motion of the wheels and the motion direction/posture of the cars, to independently modulate the movability/staticity and the naturalness of the visual stimuli. The wheels were either static or rotating clockwise. It is assumed that the cars could be recognized as movable in the external world when the wheels were rotating, whereas the cars would be recognized as static with the static wheels. To modulate the perceived naturalness of the stimuli, we varied the motion direction and the posture of the cars as well; cars presented upright and moving horizontally were assumed to be perceived as natural. This kind of visual stimulation resembles a vivid, dynamic wallpaper. We assumed that as the present time of this stimulus increases, participants will associate these motion stimuli with scenes in life, so that the stimulus is not only a dynamic wallpaper, but also has a meaning that is closer to reality and nature. Unnatural stimuli were made with cars moving vertically or presented upside-down (Riecke et al., 2006). In Experiment 2, we added schematically drawn road scenery as a contextual background. The addition of the road scenery was supposed to enhance the observer's perception that the cars

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were moving on a static road, affecting their interpretation of the movability/staticity of the visual stimuli.

3 Methods

3.1 Ethics Statement

The study was pre-approved by the Ethics Committee of Kyushu University and written informed consent was obtained from all participants before starting the two experiments.

3.2 Apparatus

The visual stimuli were presented on a Plasma display (3D Viera 65-inch, Panasonic, Japan, with 1920 × 1080-pixel resolution at a 60-Hz refresh rate) (see Figure 1e) and controlled by a computer (MacBook Pro Retina, 13-inch, Mid 2014). The visual angles of the display subtended 71 degrees (vertical) × 103 degrees (horizontal) from the viewing distance of 57 cm. Experiments were conducted in a darkened experimental room where the display was the sole light source.

3.3 Participants

Fifteen naïve volunteers (6 men and 9 women), gathered via convenience sampling participated in two experiments. Their average age was 23.9 years (ranging from 21 to 27). They were graduate or undergraduate students of Kyushu University, Japan, and all had normal vision or corrected-to-normal vision. They were not aware of the purpose of the experiment.

3.4 Procedure

There were 9 different stimulus conditions in Experiment 1 and 6 different stimulus conditions in Experiment 2. The experimental trials in each experiment were presented in a randomized order in one block, with each block repeated 3 times. In this study, the Random class was used, which is a pseudo-random number generation algorithm in Unity. This can make the randomized array present stimuli in a randomized order. The task of the participants was to press a button when they perceived vection. Elapsed time from the visual stimulus onset until the first button press was recorded as the latency of vection, and the total duration of button pressing was recorded as the duration of vection. After presentation of each stimulus, participants reported their subjective estimated vection magnitude using a 101-point rating scale, that is, 0 (no vection at all) to 100 (strongest vection).

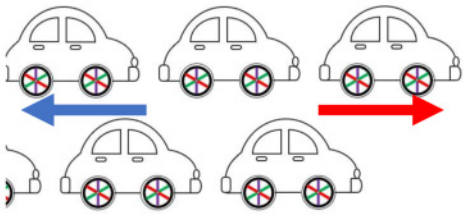
3.5 Stimuli

The visual stimuli employed in Experiment 1 consisted of a multiple number of cartoon cars, against a blank background, moving in the same direction (see Figure 1), that is, forward, backward, and upward. We also provided an additional condition in which the cars were presented upside down and moved forward (the inverted condition). We assumed that the forward and the backward conditions would be recognized as natural because we experience these in daily life, whereas the upward and the inverted conditions should be considered unnatural. In all conditions, the cars' fronts were directed to the right (thus, the cars moved rightward in the forward and inverted condition, and moved leftward in the backward condition).

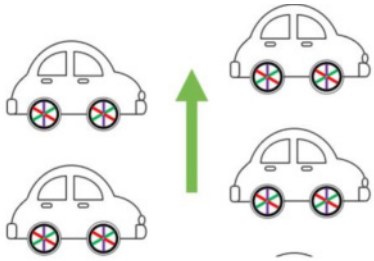
In each direction condition, the wheels of the cars were set to rotate clockwise or remained static to see if the perceived movability of the cars would have any effect on vection; the stimuli with the rotating wheels implied that the cars were movable, whereas the static wheels implied that the cars were static in the external world. In total, we employed 8 different stimuli with cartoon cars, consisting of 4 levels of motion direction (forward, backward, upward, and inverted), each with 2 kinds of wheel motion (rotation and static). The ninth stimulus was a control condition, in which black ovals, instead of cars, moved rightward. These black ovals had the same size as the cars.

In the car stimuli, on average, 4–5 cars were presented on the display, forming 2 rows of cars. The size of each car was 10.52 degrees in length and 6.83 degrees in height. The visual stimulus was presented on the entire area of the display. The speed of the moving cars

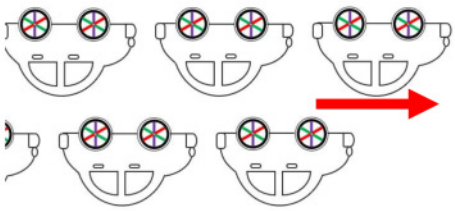
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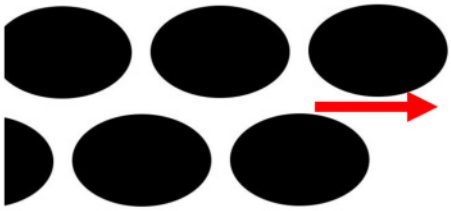
(a) Forward condition (red arrow), (the car moves from left to right). Backward condition (blue arrow), (the car moves from right to left).



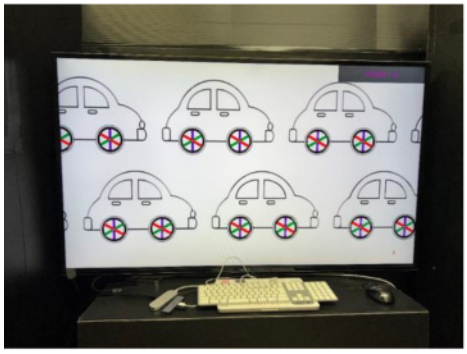
(b) Upward condition.
(the car moves from down to up).



(c) Inverted condition (a normal car flipped 180 degrees; the car moves from left to right).



(d) Control condition (a black oval moves from left to right).



(e) Apparatus in this study (Plasma display 3D Viera 65-inch, Panasonic, Japan, with 1920 × 1080-pixel resolution at a 60-Hz refresh rate).

Figure 1. *(a)–(d): The stimuli used in Experiment 1. Each arrow indicates the motion direction of cars or ovals. In stimuli with car movement, the wheels of cars were either rotating or static. (e): The apparatus used in Experiments 1 and 2.*

was 8.3 degrees/s (in the center of the screen), and the speed of the wheel rotation was 0.2 rotations/s. The background of the stimuli was white with a luminance of 13.5 cd/m^2. The cars were drawn in black lines with a luminance of 0.3 cd/m^2. The axles were drawn in black, red, purple, and green to facilitate the visibility of the

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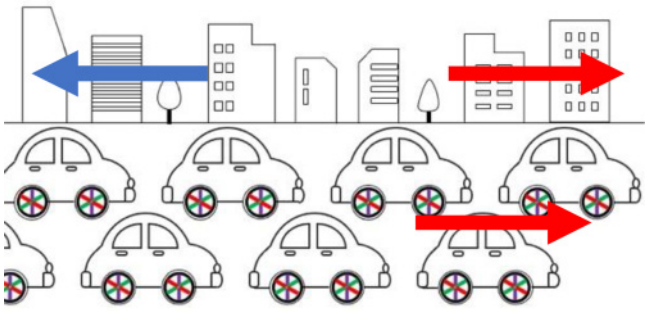


Figure 2. *The stimuli used in Experiment 2. Cars in two rows moved always rightward and the road scenery moved rightward (same direction), leftward (opposite direction), or was still.*

wheel rotation. Stimulus duration was set to 30 seconds for all experimental trials.

The visual stimuli used in Experiment 2 were modified from those used in Experiment 1 in the following way. We introduced "road scenery" as a background into the visual stimuli as indicated in Figure 2. The independent variables manipulated in this experiment therefore were the motion of the road scenery and the rotation of the wheels. The cars occupied the bottom two-thirds of the screen and the road scenery occupied the top one-third. The size of one car was the same as that in Experiment 1, and the cars were always set to be upright and moving rightward. There were three levels of road scenery motion, namely, motion in the same direction (rightward), in the opposite direction (leftward), or still. In the same-direction and the opposite-direction conditions, the motion speed of the road scenery was identical to that of the cars (8.3 deg/s). As in Experiment 1, the car wheels were either rotating or static. In the rotating condition, the wheels were set to rotate clockwise.

4 Findings

Figure 3 indicates average vection latency, duration, and estimated magnitude for each stimulus condition obtained in Experiment 1. Two-way analyses of variance (ANOVA) revealed that the main effect of the motion direction of the cars was significant for the three indices of vection strength: latency, $F(3, 42) = 5.41$, $p < 0.01$, $\eta_p^2 = 0.28$; duration, $F(3, 42) = 7.62$, $p < 0.01$, $\eta_p^2 = 0.35$; estimated magnitude, $F(3, 42) = 10.49$, $p < 0.01$, $\eta_p^2 = 0.43$. The main effect of the wheel rotation and the interaction between the two independent variables were not significant for the three indices: Main effect of wheel rotation: latency, $F(1, 14) = 0.03$, $p = 0.86$, $\eta_p^2 < 0.01$; duration, $F(1, 14) = 2.47$, $p = 0.14$, $\eta_p^2 = 0.15$; estimated magnitude, $F(1, 14) = 1.11$, $p = 0.31$, $\eta_p^2 = 0.07$; Interaction (car motion direction × wheel rotation): latency, $F(3, 42) = 1.00$, $p = 0.40$, $\eta_p^2 = 0.07$; duration, $F(3, 42) = 1.58$, $p = 0.21$, $\eta_p^2 = 0.10$; estimated magnitude, $F(3, 42) = 1.46$, $p = 0.24$, $\eta_p^2 = 0.09$.

Post hoc pairwise comparisons with Fisher's LSD test (alpha = 0.05) for the main effects of motion direction of the cars revealed that shorter vection latency was obtained in the forward condition ($p < 0.01$) and the backward condition ($p < 0.01$) as compared to the inverted condition, which indicates vection was more profound in the forward and backward condition than in the inverted condition. Also, longer vection duration was obtained in the forward condition ($p < 0.01$), in the backward condition ($p < 0.01$), and in the upward condition ($p < 0.05$), as compared to the inverted condition. Longer vection duration was also obtained in the backward condition ($p < 0.05$) as compared to the upward condition. Together, this indicates that vection was more profound in the forward and backward condition, together with the upward condition, than in the inverted condition. Meanwhile, the backward condition induced more robust vection than the upward condition. Finally, higher estimated magnitude was obtained in the forward condition ($p < 0.01$) and in the backward condition ($p < 0.01$) as compared to the inverted condition. A higher estimated magnitude was also found for the backward condition ($p < 0.05$) as compared to the forward condition, as well as for the backward condition compared to the upward condition ($p < 0.01$). Together, this indicates that the forward and backward conditions induced more robust vection than the inverted condition, and that the backward condition induced the most robust vection compared to the other conditions. It should be noted that no significant difference was found between forward and upward

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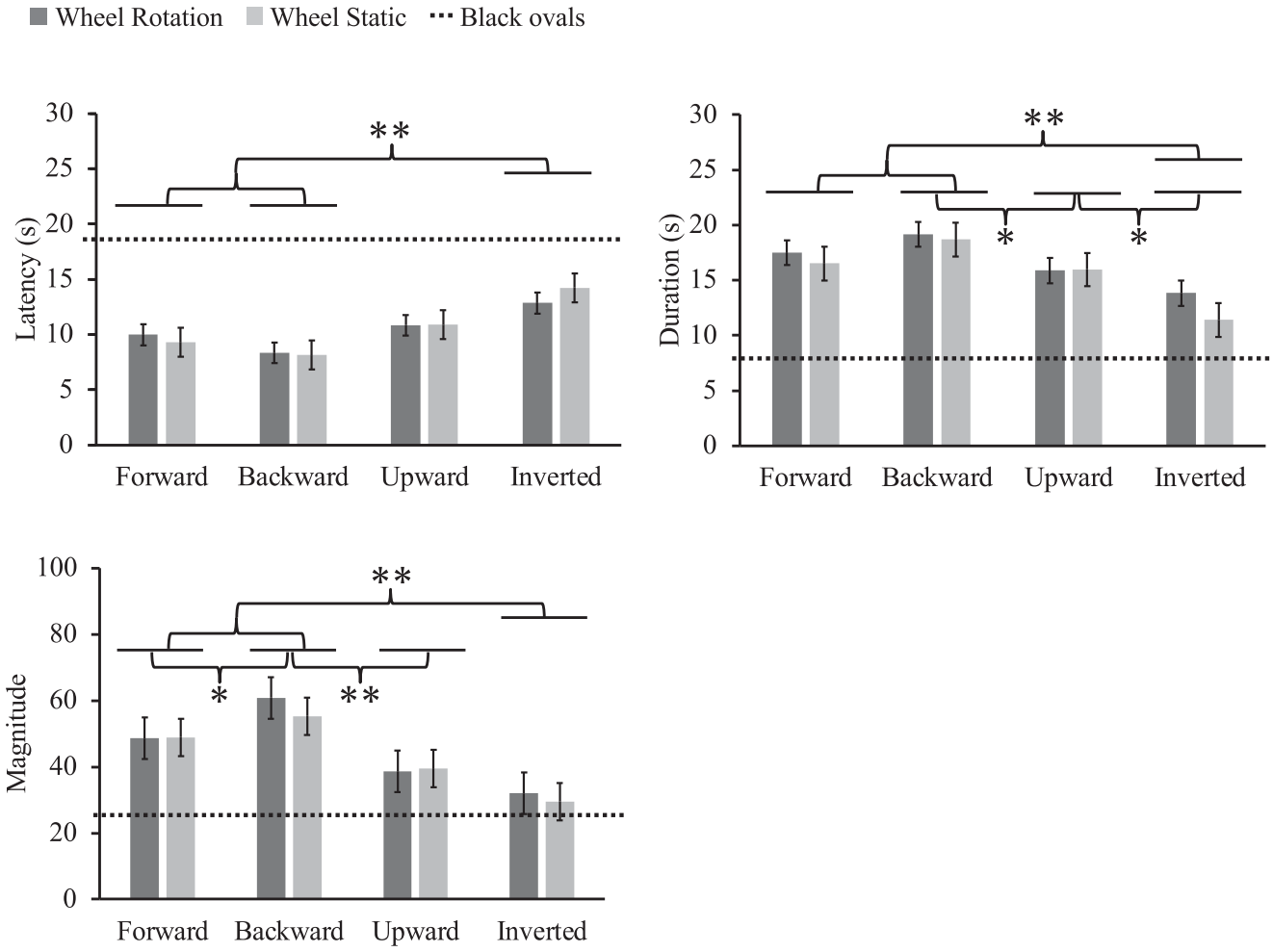


Figure 3. *Averaged latency, duration, and estimated magnitude under each stimulus condition obtained in Experiment 1 ($N = 15$; **, $p < 0.01$; *, $p < 0.05$; error bars indicate SEs).*

conditions, suggesting they were equally effective in inducing vection, though the forward condition tended to induce a shorter latency, a longer duration, and a larger estimated magnitude than the upward condition. Lastly, the control condition, in which the visual stimulus was composed of objects without real-life meanings (i.e., the ovals), yielded the longest latency, the shortest duration, and the lowest estimated magnitude compared with each other experimental condition consisting of stimuli with real-life meaning (i.e., cars). This shows that the more natural the stimulus is to the participants, the stronger the vection intensity. Naturalness is an important factor affecting the vection intensity. In addition, it can be seen from Figure 3 that the vection intensity of the forward and backward motion conditions is also higher than that of the upward and inverted conditions, because the forward and backward conditions are more common in life while the upward and inverted conditions are not common in life and therefore feel unnatural.

Figure 4 indicates average vection latency, duration, and estimated magnitude for each stimulus condition obtained in Experiment 2. For the three vection strength indices, two-way ANOVA revealed that the main effect of the motion direction of the road scenery was significant: latency, $F(2, 28) = 17.95$, $p < 0.01$, $\eta_p^2 = 0.56$; duration, $F(2, 28) = 19.07$, $p < 0.01$,

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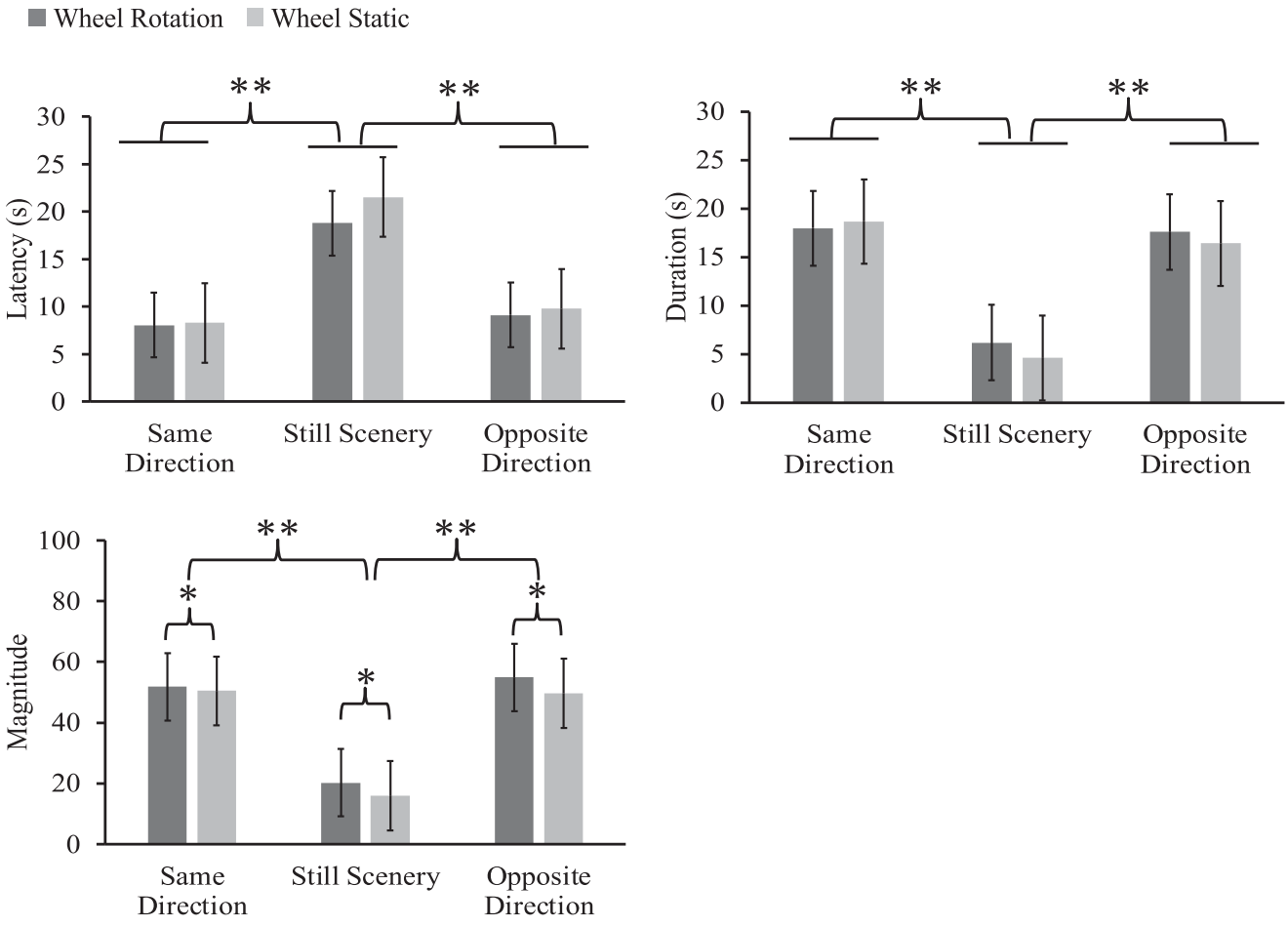


Figure 4. *Averaged latency, duration, and estimated magnitude under each stimulus condition obtained in Experiment 2 (N = 15; **, $p < 0.01$; *, $p < 0.05$; error bars indicate SEs).*

$\eta_p^2 = 0.58$; estimated magnitude, $F(2, 28) = 21.41$, $p < 0.01$, $\eta_p^2 = 0.61$. The main effect of the wheel rotation was not significant for vection latency and duration: latency, $F(1, 14) = 2.16$, $p = 0.16$, $\eta_p^2 = 0.13$; duration, $F(1, 14) = 1.49$, $p = 0.24$, $\eta_p^2 = 0.10$, but was significant for estimated magnitude, $F(1, 14) = 8.21$, $p < 0.05$, $\eta_p^2 = 0.37$. The interaction (road scenery motion direction × wheel rotation) was not significant for all indices: latency, $F(2, 28) = 0.82$, $p = 0.45$, $\eta_p^2 = 0.06$; duration, $F(2, 28) = 1.09$, $p = 0.35$, $\eta_p^2 = 0.07$; estimated magnitude, $F(2, 28) = 0.36$, $p = 0.70$, $\eta_p^2 = 0.03$.

Post hoc pairwise comparisons with Fisher's LSD test (alpha = 0.05) for the main effects of motion direction of the road scenery revealed that shorter latency, longer duration, and higher estimated magnitude were obtained in the same-direction ($p < 0.01$) and opposite-direction ($p < 0.01$) conditions as compared to the still scenery condition. The same-direction and opposite-direction conditions thus induced more robust vection than the still scenery condition for all three indices. As for estimated magnitude, a higher score was obtained in the wheel rotation condition than in the wheel static condition ($p < 0.05$). Thus, the wheel rotation condition induced vection more convincingly than the wheel static condition when the static or moving road scenery was added to the visual stimulus. It indicated that the clockwise rotation of the wheels, which was consistent with the rightward movement of the cars, increased the vection strength. This is inconsistent with the

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movability/staticity hypothesis because the rotating wheels certainly should have increased the likelihood that the cars were considered as moving by themselves in the external world, which should have hindered vection. When presented along with the background stimulus (i.e., the road scenery), however, it is likely that the background would dominate visual self-motion perception, and the movability/staticity of other visual objects (e.g., the cars in this experiment) should be negligible. Rather, the facilitative effect of the wheel rotation on vection would stem from the improved "naturalness" of the visual stimulus, not from its immobility; moving cars against road scenery are likely perceived as more natural when presented with rotating wheels instead of static wheels. Although weaker than the movability/staticity effect of the strong spatial frame of reference (i.e., the road scenery), the result of Experiment 2 thus suggests that the naturalness of the visual inducer can facilitate the observer's visual self-motion perception, following the naturalness hypothesis.

5 Discussion

Based on previous research, it is known that if vection strength increases, vection latency decreases, vection duration increases, and the estimated magnitude should be higher (e.g., Seno et al., 2017, 2018). Together, Experiment 1's results thus show that the (natural) forward and backward conditions induced the strongest vection, while the (unnatural) inverted condition induced the weakest vection in terms of stimuli with real-life meaning (i.e., cars).[1] Weaker vection induced in the control condition (as compared with the experimental conditions) would also be consistent to the naturalness hypothesis, because meaningless ovals would be less natural as compared with cars in any motion direction and posture. In general, these motion stimuli are composed of representations of things contained in reality. Certain dynamic wallpapers also use stimuli with natural meanings, so stimuli that are consistent with life will automatically be regarded as providing more natural stimulation. As opposed to what can be expected based on the movability/staticity hypothesis, Experiment 1 failed to find a significant difference in vection strength between the conditions where the wheels were set to rotate (which implied the cars were moving) or remained static (which implied the cars were static). Earlier research has shown that consistent and inconsistent local rotations of visual elements convoluted into global rotation might be ignored by participants (Nakamura, 2015). It is therefore possible that the fine and detailed rotation of the wheels was ignored by the observers. One of the possible reasons why the effects of wheel rotation might have been discounted or ignored is the lack of information indicating that the cars were moving on a road against a scenic background. Without such a background, the observers somehow might have had an impression that the wheels were "slipping on the spot," and the cars

[1]We also conducted a post-hoc observation to confirm the perceived direction of self-motion. Five naïve observers, who took part in the main experiment, also participated in the post-hoc observation. They were asked "in which direction did you feel you moved?". There were five possible responses, that is, (1) upward, (2) downward, (3) leftward, (4) rightward, and (5) No self-motion. In rightward conditions, two participants reported leftward self-motion (40%) and one participant reported rightward self-motion (20%). The fourth participant reported leftward self-motion under wheels rotation but no self-motion under wheels static (20%), while the fifth participant reported rightward self-motion under wheels rotation but leftward self-motion under wheels static (20%). In leftward conditions, three participants reported rightward self-motion (60%), and the other two participants reported rightward self-motion under wheels rotation, while under wheels static one of them reported no self-motion (20%) and the other one reported leftward self-motion (20%). In upward conditions, four participants reported downward self-motion (80%) and the fifth participant reported upward self-motion (20%). In inverted and oval conditions, three participants reported leftward self-motion (60%), another participant reported rightward self-motion (20%), while the fifth participant reported no self-motion (20%). Notably, the participant who reported no self-motion was always the same participant. Most observers reported that self-motion was perceived in the opposite direction against the car motion in each experimental condition. That is, leftward self-motion was perceived in the forward and the inverted condition, rightward self-motion was perceived in the backward condition, and downward self-motion was perceived in the upward condition. While there also were exceptional cases in which just one observer rarely perceived any self-motion, the results were consistent with the pervious vection studies; visual self-motion was mostly induced in the opposite direction to the visual inducer.

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themselves were static in the external scene. In Experiment 2, we further examined the effects of wheel rotation in conditions where contextual background, that is, road scenery, was added in order to better convey the real-life meaning of moving cars.

Experiment 2 indicated that in the conditions with the moving road scenery (the same- and the opposite-direction conditions), more compelling vection was induced than with the still scenery condition. When the still road scenery was presented, the observer's self-motion perception was highly suppressed, irrespective of the presentation condition of the moving cars. Vection thus appears to be determined by the motion of the road scenery, not by the motion of the cars.[2] This was consistent with previous research indicating that visual self-motion perception is dominated by the background stimulus, which is assumed to be static in the external space (Howard & Heckmann, 1989; Seno et al., 2009). The present results thus can be consistently explained by the movability/staticity hypothesis. In addition, the effect of the wheel rotation was significant only for vection estimated magnitude, but not for latency or duration. This might be related to the fact that magnitude estimation of vection is highly sensitive to manipulation of cognitive factors in vection experiments, as compared with latency or duration (Seno, Abe, & Kiyokawa, 2013; Seno, Ito, & Sunaga, 2009; Seno, Sawai, et al., 2017; Seno, Murata, et al., 2018; Palmisano et al., 2015). In Experiment 1, in which the visual stimulus did not include the additional road scenery, we did not confirm a significant effect of wheel rotation. It is possible that the effect of local wheel rotation is originally weak, and could not emerge without contextual background, that is, the road scenery, which strongly implied that the cars moved in the external environment. (Please note that although the effect of the wheel rotation was significant, it was much weaker than the effect of the road scenery, and there was no significant interaction between the two independent variables.)

The results of the two psychophysical experiments reported here thus demonstrate that both the naturalness and the movability/staticity of the visual stimuli can significantly affect vection. Their relative influence, however, is modulated in accordance with the stimulus setting. In Experiment 1, where the visual stimulus was composed only of cars without road scenery, vection strength was affected by the naturalness of the visual stimulus much more than by movability/staticity of the objects in the stimulus. This can be consistently explained in accordance with the naturalness hypothesis: more natural visual stimuli can induce stronger vection. Thus, the inverted cars stimuli used in Experiment 1 are supposed to be perceived as unnatural (see also, e.g., Kim & Marlow, 2016, for a discussion on inverted images), because we always expect them to be upright and rarely can see cars in an upside-down position due to the usual frame of reference (i.e., the earth's ground). Previous studies have used other methods to vary the naturalness of stimuli, such as their smoothness (by using a multi-flash protocol) (Fujii et al., 2018), the completeness of the stimulus (by using the mosaic method) (Riecke et al., 2006), the abstraction level of the stimuli (Guo et al., 2022), and their surface properties via computer graphics technology (Morimoto et al., 2019). The use of natural real-world stimuli (e.g., real street scenes, room scenes, and believable ground information)

[2]Similar to Experiment 1, we conducted a post hoc observation in order to assess vection direction. The 5 observers who participated in the previous post hoc observation also took part here. The procedure was the same as in Experiment 1. In still conditions, all participants reported they did not perceive continuous and unidirectional visual self-motion (100%). In same-direction conditions, four participants reported leftward self-motion (80%), and the fifth participant reported no self-motion with rotating wheels but leftward self-motion with static wheels (20%). In opposite-direction conditions, four participants reported rightward self-motion (80%), and the fifth participant reported rightward self-motion with rotating wheels but leftward self-motion with static wheels (20%). Notably, the participant who reported different assessments from the other four in same- and opposite-direction conditions was not always the same participant. Above all, although it is noted that visual motion presented in the lower visual field induces stronger vection compared with that in the upper visual field (Fujimoto & Ashida, 2020), suggesting that the perceived self-motion direction might be dominated by the cars, in this study, most observers reported that self-motion was perceived in the opposite direction against the motion of the road scenery (that is, leftward and rightward self-motion was perceived in the same- and the opposite-direction conditions, respectively). On the other hand, no observer reported visual self-motion perception without direction in the opposite conditions (Seno et al., 2012).

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affected the stimuli's naturalness. These studies similarly found that the higher the naturalness of the visual stimuli, the stronger the vection (Richards et al., 2004; Riecke et al., 2006; Sato et al., 2020; Schulte-Pelkum et al., 2003).

On the other hand, when the background (i.e., the road scenery) was introduced into the visual stimulus in Experiment 2, the (im)movability of the stimulus objects became the dominant factor in generating vection. This is similar to previous vection studies. For example, Ogawa and Seno (2014) revealed that natural visual objects, such as feathers, petals, or leaves, which can be considered as movable in the external world, were less effective in inducing vection as compared with visual objects without specific real-life meanings (e.g., random dots). In this case, the movability/staticity interpretation of the visual stimulus might take a priority, obscuring the effects of stimulus naturalness. Experiment 2 also indicated that vection strength became weaker when the road scenery was still, as compared to moving, irrespective of the motion direction of the cars. This supports the movability/staticity hypothesis: visual objects which are assumed to be externally static (e.g., the road scenery) have greater impact on visual self-motion perception than movable objects (e.g., cars). Although we expected more robust vection in the opposite-direction condition than in the same-direction condition, because foreground object motion can increase the perception of self-motion generated by background motion, even when both are in the opposite direction (Kim & Tran, 2016), the present study did not show any significant difference between the same- and opposite-direction conditions. We tend to attribute this to the larger area of the uniformly-moving stimulus in the same-direction condition, since vection strength increases linearly with the size of the area in which the moving pattern is presented (e.g., Nakamura & Shimojo, 1998; Nakamura, 2001, 2008).

Although we tentatively conclude that the perceived naturalness and the assumed immobility of the visual inducer are two important cognitive factors in visual self-motion perception, their relative contributions on vection are not clearly understood yet. Actually, the present study used cartoons as the stimuli instead of real video footage because that enabled us to independently manipulate the wheel motion in a systematic and controlled way. However, not using images of real cars indeed limits the present findings and meaning. Thus, in future studies, we should utilize stimuli in which both their naturalness and their mobility are manipulated systematically and quantitatively, to better clarify their individual effects on vection.

In addition, the results of this study can open new research angles and methods for the relationship between vection and presence in virtual reality. With the development of virtual reality technology, more and more studies have examined the role of vection in virtual reality. Self-motion perception itself is a process involving the processing of multisensory cues, such as visual and vestibular cues (Zhou & Gu, 2023). Vection is generally believed to improve simulator fidelity and enhance virtual reality applications and so on. Since an important indicator of virtual reality is the sense of presence and immersion, researchers usually study the role of vection in virtual reality together with the sense of presence and immersion. It was found that there is a positive correlation between the intensity of vection and immersion and the sense of presence. The findings of this study further expand the means of enhancing vection experience. For example, real-life objects and motion stimuli can be combined and cleverly presented in the virtual reality world. In this way, the boundary between the virtual world and the real world will become increasingly blurred, and the individual's experience in the virtual world will be more realistic, which will be helpful in many fields, such as psychotherapy in the virtual world and so on (Emmelkamp & Meyerbröker, 2021).

Another important indicator of virtual reality world is motion sickness (induced by motion simulation, accompanied by symptoms such as nausea, dizziness) and cybersickness (induced by the device, symptoms are similar to motion sickness) (Mazloumi Gavgani et al., 2018). Previous research found that motion sickness is positively correlated with presence and frequency of vection (Keshavarz et al., 2023). In addition, previous research has found that the impact of cybersickness on user experience should be more accurately detected during user immersion rather than after (Kourtesis et al., 2024). And researchers are also looking for ways to reduce motion sickness or cybersickness through vection (Kim et al.,

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2023; Matsumoto & Zhang, 2022). Therefore, in future research, we can use virtual reality to present more natural stimuli or scenes to increase the user's vection intensity, moderate the motion sickness, and enhance the sense of presence.

6 Conclusion

In this study, we examined the influence of cognitive factors on visual self-motion perception by employing stimuli with a real-life meaning, consisting of moving cars with wheel rotation and moving road scenery. The results of the two psychophysical experiments demonstrated that both the naturalness and the movability/staticity of the visual stimuli could significantly affect vection. This suggests that the more natural the stimulus meanings were, the stronger the vection was. Vection is self-movement in the virtual world and is closely related to the sense of presence. It is a feasible and effective application prospect to enhance the vection experience by changing the naturalness of the stimulus to further increase the sense of presence and immersion. Therefore, the perceived naturalness and the assumed staticity of the visual inducer are two important cognitive factors in visual self-motion perception and presence in the virtual world.

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Data Availability Statement

The data that support the findings of this study are available upon request to the corresponding author.

Conflict of Interest

The authors have no conflict of interest to declare that are relevant to the content of this paper.

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