VECTION (THE SELF-MOTION ILLUSION) IN VIRTUAL REALITY

By

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CHAPTER I

Introduction

Vection is an illusion of movement, a phenomenon in which someone can feel like they are moving while there is no actual movement (Wood, 1895; Mach, 1875). Many people experience this phenomenon in real life: for example, when sitting in a car and observing another car moving forward to pass by him or her, a person may have a strong illusion of suddenly moving backwards, even though the car is still stationary. This sensation can also occur in a stationary train when there is a train accelerating to move on an adjacent track. Consequently, vection is also named as the self-motion illusion (Mach, 1875; Fischer and Kornmüller, 1930; TschermaK, 1931).

In contrast to the real world, virtual environments can not always offer a compelling and strong sensation of movement, resulting in a poor and unreliable experience in the virtual reality (VR). One way to solve this problem is to employ motion-tracking devices in the virtual environment, especially in a large-tracked space, allowing subjects to move and thus bringing a more believable feeling of involvement and motions. However, this solution presents its own problems as it requires a large space for subjects to move in and tracking systems for such spaces are typically expensive (Riecke et al., 2011, 2015). Inducing a sense of vection, however, could help to provide a compelling sensation of involvement and movement without those devices in order to reduce our overall costs of VR, including interference and transformation costs (Riecke, 2010; Riecke et al., 2012). According to this idea, a self-motion illusion could compensate for our sensation of movements. Furthermore, subjects would not need to walk in the real world any more while getting a corresponding sensation of movement in the virtual environment. Consequently, self-motion illusions could induce compelling sensations of motions in the virtual environment without full physical movements in the real world.

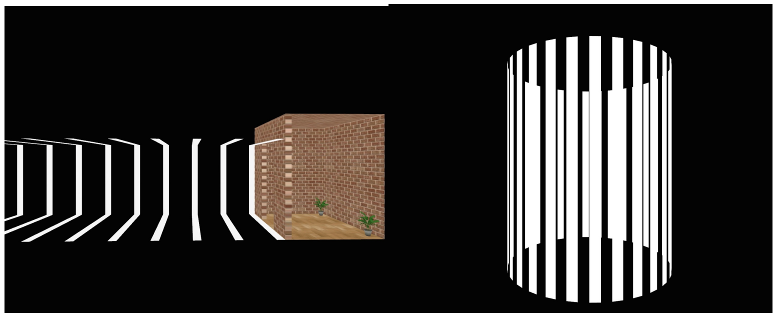
Vection can be induced by moving objects, like the car illusion and train illusion mentioned previously (Mach, 1875; Andersen and Braunstein, 1985; Wood, 1895). Andersen and Braunstein (1985) presented that a perception of vection can be induced by visual cues alone, even when subjects are stationary. In addition to moving stimuli, however, other factors can also contribute to an induction of vection including auditory, tactile, and biomechanical cues, or galvanic stimulation (Riecke, 2010). Such cues can provide a believable sensation and involvement in the VR, resulting in a life-like virtual world to subjects. Furthermore, Riecke mentioned that stimulus velocities, stimulus sizes, central and peripheral visual field, optimal spatial frequency, density of moving stimulus, different kinds of vection, simulation of viewpoint jitter and perceived rigidity of optic flow field could also induce or facilitate self-motion illusions.

Based on directions of perceived vection, self-motion illusions are divided into linear, circular and curvilinear vection (Trutoiu et al., 2009). Linear vection is induced by contrast objects that are moving vertically or horizontally, while circular vection is induced by rotation of contrast cues. In linear vection, subjects are stationary and observe a contrasting object moving either up, down, left, right, forward or backward. Up-down vection is also known as elevator vection while the car illusion indicates forward-backward vection or left-right vection. An optokinetic drum is a circular curtain with black-white stripes, moving at different velocities and a clockwise or counter-clockwise manner, inducing circular vection. Subjects are required to sit or stand statically while the optokinetic drum is rotating. First, they probably perceive surrounding motions, i.e. the movement of the optokinetic drum. After a while, subjects should have a sensation of a circular vection. The first time that a subject feel a self-motion illusion is called the vection onset latency.

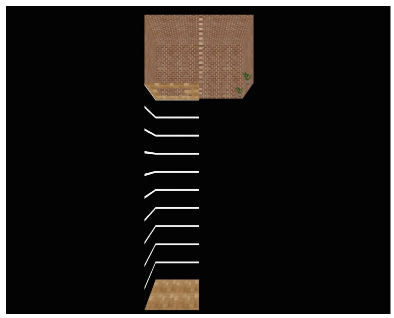
According to prior studies, it is not easy to induce vection in virtual reality. The biggest challenge to induce vection in VR is that not all modalities are simply simulated easily (Riecke, 2010). Subjects sometimes insist that they do not feel like being involved in a virtual environment because of an inappropriate simulation of objects or background, bringing a strong and believable sensation that they are not in a virtual environment. On the other hand, some visual, auditory or tactile cues might also disturb the experience of exploring a virtual environment, providing a conflict between a self-motion illusion and a stationary sensation. Even if you have a little sensation of vection, those cues could offer you a conflict that you are actually stationary rather than moving. Meanwhile, field of view (FOV) could contribute to vection, resulting from central visual and peripheral visual cues. Brandt et al. (1973) presented that subjects cannot get self-motion illusions when stimulation of central visual field was limited up to 30° in diameter. In VR, however, subjects cannot have a wide field of view compared to the real world, because of wearing a head-mounted display (HMD). The Oculus Rift, a wide FOV HMD, was employed in this study; it has a FOV of 90° horizontal and 110° vertical.

In this study, we worked on a comparison of circular vection between VR and the real world. In the real world, an optokinetic drum, a circular curtain with black and white stripes, was employed to induce circular vection. Subjects are required to sit or stand in the center of the circular drum while the curtain rotates in a clockwise or counterclockwise manner at different velocities. We also compared stimuli induced purely through the Oculus HMD, that would give us both circular and linear vection. We created three virtual environments including virtual horizontal, virtual circular and virtual vertical environment (Figure I.1). A virtual circular stimulus was simulated to be similar to the real optokinetic drum, while the virtual horizontal and virtual vertical stimulus, representing linear vection in VR, were created based on a resizable hallway or pit room with black and white stripes. Subjects were asked to report vection-onset latency, and give ratings of intensity and convincingness of vection in each trial.

The purpose of this research is to effectively simulate vection in the virtual environment and measure vection based on subjective questionnaires using commodity level equipment, compared to the vection in real world. We employed Oculus Rift, a low-cost, wide field-of-view head-mounted display (110° diagonal), to render our virtual environments. Unfor-



(a) Horizontal Environment (b) Circular Environment



(c) Vertical Environment

Figure I.1: Three virtual environments.

tunately, even though an Oculus Rift was employed in this study, subjects still do not have a full FOV compared to that of the real world. Consequently, we simulated a limited FOV (same FOV in Oculus Rift) with real-world stimulus to demonstrate the influence of FOV in the real-world circular vection. We hypothesized that a full FOV could induce more reliable, compelling, and faster vection than a limited FOV in the real-world circular stimulus. Besides, display factors could play key roles in inducing a virtual environment. As a result, we would expect that real-world vection could be more compelling and induced faster compared to VR vection. We believe that the importance of this work is that the ability to simulate the illusion of movement is another step towards the creation of compelling virtual environments and 3D computer games.

In this paper, Chapter II will introduce a background on vection with related work. Our vection stimulus (real-world stimulus and VR stimulus), experimental design, and procedure will be presented in Chapter III. Chapter IV describes analysis, results, and the discussions based on our experiments. Finally, Chapter V contains some concluding remarks.

CHAPTER II

Background

Self-motion illusion occurs in a moving visual stimuli, which has been described more than a century ago (Mach, 1875; Wood, 1895; Fischer and Kornmüller, 1930; TschermaK, 1931; Brandt et al., 1973; Berthoz et al., 1975; Giannopulu and Lepecq, 1998; Riecke, 2010). Mach (1875) used an optokinetic drum with repeated black-white stripes in his experiment, simulating circular vection in the real world. An opotokinetic drum is a circular curtain with black-white stripes, rotating at different velocities and directions. Subjects were asked to sit or stand at the center of circular drum and observe the rotation of the stripes. Wood (1895) employed a swing in a room to demonstrate circular vection. The swing was at rest while the room with furniture fastened was in circular movement. Vection is termed circular vection, linear vection, or curvilinear vection based on the perceived motion, respectively (Fischer and Kornmüller, 1930; TschermaK, 1931; Riecke, 2010).

Unlike the circular vection observed by the rotation of an optokinetic drum, linear vection focuses on the translation (Lishman and Lee, 1973; Berthoz et al., 1975). According to the direction of motions perceived by subjects, linear vection can be categorized into vertical and horizontal vection. Up-down vection perceived motion is called vertical vection, considering a veritcal gravito-inertial vector. In daily life, one may have up-down vection in a transparent stationary elevator while observing the adjacent elevator going up or down. Left-right and forward-backward perceived motions could both indicate horizontal vection. Berthoz et al. (1975) presented characteristics of sensation of horizontal vection in a seated object. Ohmi and Howard (1988) suggested an illusory forward self-motion induced by a looming display, showing that forward vection was controlled by the display perceived as the background.

Circular vection, for most subjects, is easily induced in a lab environment compared to linear vection (Trutoiu et al., 2009). Trutoiu et al. (2009) suggested that linear vection was less convincing compared to circular vection when presented through a panoramic projection. Meanwhile, circular vection around the earth-vertical axis (yaw) is much more easily induced than earth-horizontal axis (pitch or roll) (Riecke, 2010), since getting a sensation of circular vection around the pitch or roll axis without full-field orientation in the lab seems quite complicated. Most circular vection studies, consequently, mainly focus on circular vection around the yaw axis. As the gravito-inertial vector is parallel with the direction of acceleration of gravity in virtual environment resulting in fewer conflicts between visual and vestibular afferents, up-down vection has been found to be induced more easily than horizontal vection (Giannopulu and Lepecq, 1998). Giannopulu and Lepecq mentioned that the vection-onset latency could be shortened by the decrease of the conflicts between visual cues and vestibular afferents in their study, comparing up-down and forward-backward vection to find faster vection onset latency and more compelling sensation on up-down vection.

Besides circular vection and linear vection, curvilinear vection is a combination of circular and linear vection. Sauvan and Bonnet (1993) demonstrated the properties of curvilinear vection and estimated the temporal characteristic of curvilinear in their study. A comparison of linear, circular, and curvilinear vection in an immersive large screen display, suggesting that curvilinear forward vection is as convincing as circular vection was presented by Trutoiu et al. (2008).

Prior studies suggested that many factors could contribute to vection. Riecke et al. (2005, 2009) indicated that adding auditory cues could facilitate circular vection, showing both perception and the presence of circular vection could be prominent. Sakamoto et al. (2004) showed that auditory cues could induce linear self-motion illusions, generating linearly moving sound images. Furthermore, Riecke et al. (2008) suggested that auditory circular vection could be enhanced via adding vibrations and physical motions. In this study, participants were seated on a hammock chair hanging above a circular treadmill with noticeable vibrations on the hammock chair and auditory cues. Whether or not subjects' feet touched the ground, vibrations and actual self-motion facilitated auditory circular vection.

In addition to auditory and vibration cues, self-motion illusions are induced by peripheral vision simulation while central vision field contributes to object motions perceived (Brandt et al., 1973; Berthoz et al., 1975; Johansson, 1977; Andersen and Braunstein, 1985). Brandt et al. (1973) employed an optokinetic drum to show that peripheral stimulus could predominate circular vection. Subjects, in their study, cannot perceive self-motion illusions when stimulation of central vision field was limited up to 30° in diameter, bringing a perception of surrounding movements. Berthoz et al. (1975) induced a linear vection based on a projection of moving images at the peripheral visual field. Meanwhile, Johansson (1977) suggested that vertical motions are induced by the limited peripheral field of retina with the optical information about stationary object over the rest of retina. He employed one vertical screen on the each side of subjects head, covering a horizontal and vertical visual angle, in order to simulate an elevator environment. Subjects were required to report their reception of going by the elevator and every change in perceived motions. Andersen and Braunstein (1985) presented an extension theory that there should be a higher level of system working on the peripheral processing in the central visual field and complicated stimulus information except a more primitive processing requiring a peripheral visual field.

To measure vection, a common solution is to use introspective measures such as subjective questionnaires (Riecke et al., 2015). Subjects are required to record the moment when vection first occurs, called vection-onset latency, the intensive and convincing ratings of vection in every trial (Trutoiu et al., 2009). If working in an accelerated stimulus, the velocity where subjects feel vection first time should be reported as well. Furthermore, subjective questionnaires are quite useful to get the intensity, convincingness, and other sensations of vection in each trial.

In this research, we compared vection in real world and virtual world, focusing on circular and linear vection. We provided a comparison between linear vection and circular vection in the virtual stimulus, using the Oculus Rift DK1 (90° horizontal and 110° vertical field of view). Three virtual stimuli were simulated based on Oculus Rift to demonstrate vection in VR. We believed that one factor–field of view (FOV), could facilitate the vection-onset latency, intensity, and convincingness of vection. To verify this idea, simulating a limited FOV in the real-world stimulus with a pair of goggles, a comparison between limited FOV and full FOV was also presented in this paper. We also indicated a comparison between circular vection in real-world stimulus and virtual stimulus with same FOV.

CHAPTER III

Experiment

In this experiment, we compared linear vection and circular vection in VR, creating three virtual stimuli through the Oculus Rift DK1. Meanwhile, simulating a limited FOV in the real world, we compared circular vection in the virtual stimulus and real-world stimulus. Furthermore, we investigated whether FOV could contribute to circular vection in the real world, comparing circular vection with full FOV and limited FOV.

III.1 Stimuli and Apparatus

III.1.1 Optokinetic Drum with Full FOV

Our optokinetic drum is a circular curtain with black and white stripes (Figure III.1). The diameter of our circular curtain is 74 inches. Meanwhile, the width of one black-white cycle is 7.75 inches. The height of curtain is 98 inches, from top to ground. Note that there is an approximately 8 inches gap from the bottom of circular curtain to the ground. Furthermore, this circular curtain could rotate in clockwise or counter-clockwise manner at different velocities.

In the optokinetic drum condition, subjects were asked to stand at the center of circular drum facing to the curtain and then circular drum rotated clockwise at a constant velocity. In this experiment, the velocity of rotation was 60°/s. Note that subjects were allowed to look left or right in this condition but they were asked not to look up and down, in order to avoid motion sickness. Subjects cannot walk around in a trial.

III.1.2 Optokinetic Drum with Limited FOV

The Oculus Rift is a wide field-of-view (FOV) head-mounted display in the virtual reality. The FOV of Oculus Rift, however, is also not as wide as our eyes in the real world. To simulate a condition with the limited FOV in the real-world stimulus compared to the Ocu-

Figure III.1: Optokinetic circular drum in real world

lus Rift, a pair of goggles was employed in this condition, simulating a limited FOV in the real world based on the Oculus Rift DK1 (Figure III.2a). Subjects were asked to stand at the center of circular drum at the beginning, wearing a pair of goggles. Then circular drum rotated clockwise at a constant velocity, 60°/s in this condition as well. Similarly, subjects were allowed to look left or right rather than look up and down. Walking in this condition was also forbidden.

To build the restricted-FOV goggles, we stood in front of a whiteboard. Knowing the FOV of Oculus Rift DK1 (manufacturers specification) and distance to the whiteboard, we marked a potential area observing on the whiteboard. Wearing a pair of goggles, one could look at this area on the whiteboard through goggles. Then we marked those boundaries on the screen of goggles, which refers to the same FOV like Oculus Rift. Finally, we covered the rest of area on the screen of goggles with black tapes, leaving two square areas uncovered like small windows. Using this pair of goggles, subjects could only see through areas uncovered on screens, resulting in a limited FOV compared to full FOV from our eyes in the real world.

(a) Goggles (b) Head cap

Figure III.2: Goggles and head-cap

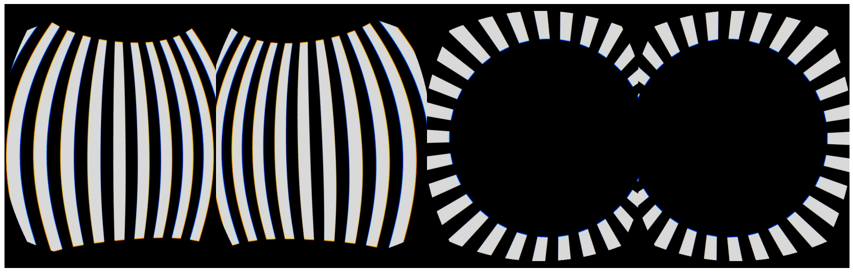
III.1.3 Virtual Circular Environment

To compare with the optokinetic drum in the real world, a virtual circular drum was simulated in the virtual environment (Figure III.3). This virtual circular drum had the same height and diameter of the real-world curtain, width of black-white stripes and velocity compared to the real one. These virtual scenes were rendered using the WorldViz Vizard rendering system and displayed on the Oculus Rift. Moreover, a tracking system Vicon was employed to track subject's position and orientation in the virtual environments.

In the virtual circular environment, subjects were asked to stand at the center of virtual circular curtain wearing the Oculus Rift and a head-cap firstly. Head-cap is used to track subjects' position through markers (Figure III.2b). Subjects could look left or right like real-world stimulus but they were asked not to look up and down. Meanwhile, they were asked to remain stationary as well.

III.1.4 Virtual Horizontal Environment

Virtual stimulus in the horizontal direction is to simulate forward-backward linear vection, where scenes could move horizontally at a constant velocity. The visual stimulus used in this condition was a room and a resizable-length hallway with black-white stripes on the walls (Figure III.4). Subjects stood at the center of virtual room first, where they were allowed to walk and look around. To begin a horizontal vection trial, subjects were in-

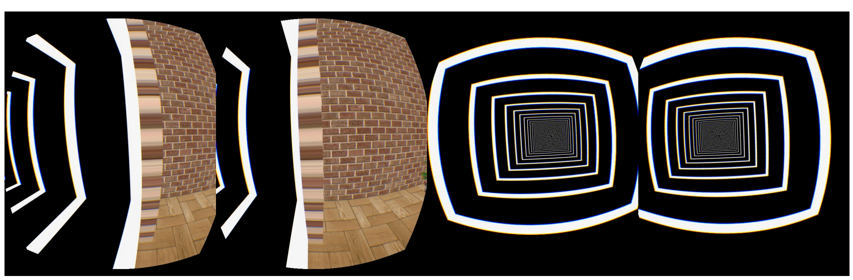


(a) Level viewpoint (b) Looking up

Figure III.3: Virtual circular environment

structed to walk into this horizontal hallway a little, facing the end of hallway. Subjects were required to face the center of hallway cross section, in order to avoid touching the walls during a trial. After pressing a button on the joystick, the hallway would move horizontally (moving backward relative to the viewpoint of subjects in this study) at a constant velocity until subjects arrived at the end of hallway. During a trial, subjects were asked not to look up and down, but they were able to look left or right.

In this virtual horizontal environment, the length of hallway was 248m. The constant velocity of hallway was 5.5m/s. The widths of black and white stripes were 0.8m and 0.2m respectively.



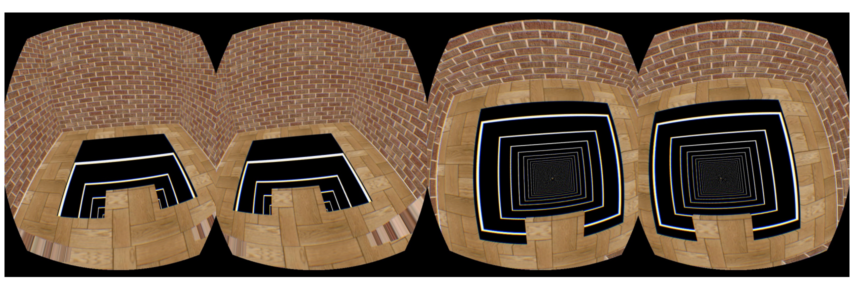
(a) Start point of hallway (b) Looking at the center of hallway

Figure III.4: Virtual horizontal environment

III.1.5 Virtual Vertical Environment

Besides a horizontal stimulus, subjects could experience vertical vection in a virtual vertical environment. The same room was simulated in this vertical stimulus like the horizontal one, but a vertical pit room was adjacent to that room instead of a horizontal hallway (Figure III.5). The pit room had a hole in the ground leading a resizable-height room below with black-white stripes on the walls. Like the horizontal environment, subjects were located at the center of the room equipped with Oculus Rift and head-cap at the beginning. They were guided into the pit room until they were close to the hole. Subjects were asked to step on the top of hole before a trial, looking down towards this vertical resizable-height room. In order to reduce their fear of standing on the top of the shaft, subjects were told that they would not fall down until pressing the button 1 on joystick. Then the pit room moved vertically (moving up in this study relative to viewpoint of subjects in this study) at a constant velocity until subjects reached the bottom of the vertical shaft. Subjects were asked not to look up and down repeatedly.

The depth of room below the hole, in vertical environment, was 294m. The constant velocity on vertical direction was 6.5m/s. The widths of black and white stripes on the wall were 0.9m and 0.1m respectively.



(a) Hole on the ground (b) Looking down the pit room

Figure III.5: Virtual vertical environment

III.2 Experimental Design

Based on a within-subject experimental design, each subject completed five conditions (two real worlds and three virtual worlds) in total: the optokinetic cicular drum with full FOV, the optokinetic circular drum with limited FOV, the virtual circular environment (VC), the virtual linear horizontal environment (VLH) and the virtual linear vertical environment (VLV). One-half of the subjects experienced the circular optokinetic drum real world (RW) first, while the other half of the subjects took the virtual reality (VR) first. Each condition had four trials for a total of 20 trials in five conditions. Each trial lasted 45 seconds and was followed by two introspective questions with a subjective evaluation on thee intensity and convincingness of the vection. Between two conditions, a short break was used to reduce any possible motion sickness and avoid side effects between two conditions. Subjects were also required to close their eyes after one trial and during the short break. Meanwhile, subjects were asked whether they were comfortable with this environment during the break. They could quit from experiments at any time if they felt uncomfortable with environment and did not want to continue with the following trials.

The ordering of the VR environments was totally counterbalanced. Consequently, the virtual environment had six combinations based on the ordering of the three virtual stimulus conditions. In each combination, two subjects (one female and one male) completed three virtual conditions. The real-world stimulus environment had two combinations based on different FOVs. One combination had six subjects (three females and three males) taking two optokinetic drum conditions. Note that we employed two labs to present the virtual stimulus experiment and the real-world stimulus experiment respectively, approximately 10 minutes walking distance apart. Most subjects performed the two conditions on different days.

At the beginning of the experiments, there was a practice session. For the virtual environment, subjects had three practice trials representing the three kinds of virtual conditions, while two practice trials were used for the real world environment. A practice trial was 45 seconds to make subjects familiar with the instructions of the experiment, joystick, real or virtual world environment, and the definition of the self-motion illusion. Note that subjects were asked to confirm their understanding of vection after each practice trial. We believe that the understanding of vection is important to the whole experiment.

III.3 Participants

A total group of 12 subjects completed our experiment. One additional subject had a problem understanding our instructions for the experiments. We excluded his data in the following data analysis. The genders of subjects were totally balanced, 6 females and 6 males. Subjects were either undergraduate students or graduate students at Vanderbilt University, being recruited on campus or online. Subject received $10 to compensate their time after the whole experiments. Subjects ranged from 24 to 36 years old, M = 27.1, SD = 3.9.

All subjects had normal or corrected-to-normal vision. One subject reported playing 3D computer games on average 2 hours one week and the rest of subjects did not play 3D computer games very often.

III.4 Interaction

Subjects employed a wireless joystick, a Logitech Freedom 2.4 Cordless Joystick (Figure III.6), to indicate vection-onset latency during a trial. Vection-onset latency is the first time that a subject feels vection in a trial. Before starting a trial, subjects were instructed to walk into a specific area, such as stepping into a hallway in the horizontal environment or stepping onto the top of the hole in the vertical environment. To start a trial, they were also required to use the joystick, pressing button 1 to make the virtual stimulus move at a constant velocity. During a trial, they could press button 2 on the joystick to stop it at any time if they had any motion sickness or felt uncomfortable with the movement of virtual environments. Once they had the first sensation of vection, they were required to press button 3 on joystick to record the onset of vection.

The Oculus Rift Development Kit 1 (DK1) was employed in this study. The FOV

Figure III.6: Joystick

of Oculus Rift DK1 is 90° horizontal and 110° vertical. It has an effective resolution of resolution of 640 × 800 per eye. Since that is not 100% overlap for both eyes, the combined horizontal resolution could be greater than 640 pixels.

Translational positions and orientations from subjects were collected by the Vicon Tracking System. Meanwhile, we used a head-cap to track the positions of translation movement while Oculus Rift is to obtain orientation data (Figure III.2b).

III.5 Procedure

At the beginning of the experiment, subjects were introduced to a definition of vection and the procedure of experiments. Then they signed a consent form and completed a pre-questionnaire before practice trials, collecting background information such as vision of both eyes and average time on 3D computer games per week. Each subject was randomly selected to experience either the virtual stimulus or real-world stimulus first. Thus one-half subjects (three females and three males) experienced the three virtual conditions first, while the rest of subjects experienced the two real-world conditions first. Subjects also received an explanation on how to use the joystick in the practice trial.

In the virtual stimulus conditions, subjects had three practice trials to make them familiar with the virtual environment, joystick and vection. The ordering of the practice trials was virtual horizontal, virtual circular and virtual vertical environment. Each practice trial was 45 seconds followed by two questions about the intensity and convincingness of a vection experienced. After one practice trial, subjects were required to confirm their understanding of the experiment procedures and vection. According to several pilot studies, the understanding of vection could be of importance to the following vection experiment.

In the virtual environment conditions, subjects were equipped with an Oculus Rift and a head-cap to track orientation and position of subjects. Subjects completed four trials for each type of vection. Before one block of vection trials, subjects were first required to calibrate the Oculus Rift. Following one trial, two introspective questions were asked based on 1-9 rating scales: (1) how intense was your sensation of self-motion?; and (2) how convincing was your sensation of actually moving?. We used 1 to indicate the least intense or convincing sensation of vection in the last trial; while 9 indicates the most intense or convincing sensation of vection. Between the two 4-trials blocks, subjects took off Oculus Rift and had a short break to reduce motion sickness. At the same time, subjects were also asked whether they were comfortable with an environment. They were able to quit from the experiment at any time if they felt uncomfortable with environments and did not want to continue with the following trials, being discarded in our analysis later. When they returned to the experiment, they were instructed to first calibrate Oculus Rift for a new condition.

In the real world conditions, subjects had two practice trials to understand the corresponding experiment instruction and vection. They had opportunities to get familiar with the joystick. At the beginning, subjects were guided to stand at the center of circular drum in the practice trial. They had two practice trials, full FOV and limited FOV with goggles. Then they completed two conditions for circular optokinetic drum in the real world, with four trials for one condition as well. After each trial, the same two introspective questions were asked to subjects based on 1-9 rating scales. Between two conditions, subjects had a short break to reduce motion sickness between two conditions, being checked whether they were sick with the environment.

After completing both experiments, subjects were thanked and received $10 to compensate for their time.

CHAPTER IV

Results and Discussion

A small number of our subjects reported minor symptoms of motion sickness during experiments, but none reported severe symptoms or withdrew from the study. The mean time in which the optical flow stimulus was applied until vection was indicated ("onset latency"), as well as values of convincingness and intensity ratings are reported in Table IV.1. In seven of 240 trials, subjects reported experiencing no vection. One subject had three reports of no vection, each among different conditions. Two of the seven reports occurred with real-world stimuli, and five occurred with virtual stimuli. Virtual horizontal vection had three reports of no vection among the seven. Each report of no vection occurred only once in each block of four trials for each condition. In each of these cases, to revise those outliers, we averaged the remaining three onset latency times and replaced the trial in which no vection occurred with the mean of the other three. We left the convincing and intensity ratings as subjects reported.

Vection onset latencies showed a large variability across subjects. The minimum onset latency for a virtual stimulus (vertical) was 1s, and the maximum was 45s (for circular). For the real-world stimuli, the minimum onset latency was 3.4s (full FOV) and the maximum was 44s (full FOV). Onset latency was analyzed in a mixed Analysis of Variance (ANOVA)

	Onset Latency (s)	Convincingness	Intensity
RW Full FOV	18.6 (2.3)	6.5 (0.5)	6.3 (0.4)
RW Lim. FOV	15.3 (1.6)	6.6 (0.4)	6.8 (0.4)
VR Horizontal	14.0 (2.5)	7.0 (0.4)	6.5 (0.4)
VR Vertical	11.8 (2.2)	6.9 (0.4)	6.5 (0.6)
VR Circular	19.7 (3.4)	6.1 (0.4)	5.7 (0.6)
Overall	15.9 (2.0)	6.6 (0.2)	6.3 (0.3)

Table IV.1: The mean onset latencies and ratings of convincingness and intensity by vection condition for Vection Experiment. Values in parentheses show standard errors of the mean.

with stimulus (experimental condition) and trial as within-subjects factor, and gender as a between-groups factor. Note that, for analysis purposes, the experimental condition consists of five distinct categories that cannot be reduced further: the circular vection with full FOV has no corresponding virtual analog, and we are unable to achieve linear vection with real-world stimuli. Thus we employ the experimental condition as we have done.

The main effect of condition was significant, $F(2,20) = 3.91$, $p = 0.037$. Figure IV.1 shows mean onset latency across the conditions of the experiment. No other effects or interactions were significant. As described previously, our interest was comparing the real-world conditions to one another, the virtual environment stimuli to one another, and the limited FOV real-world stimulus to virtual circular vection. We performed a series of paired-sampled t-tests to examine these conditions, controlling for experimental error rates using false discovery control (O'Keefe, 2003; Benjamini and Hochberg, 1995; Glickman et al., 2014). The results of this series of t-tests showed that the mean onset latency for the virtual circular stimulus was significantly longer than for both the virtual horizontal stimulus, $t(11) = -2.53$, $p = 0.028$, and for the virtual vertical stimulus, $t(11) = -2.70$, $p = 0.020$.

From Table IV.1, the overall ratings for how convincing and intense the vection seemed were rated reasonably highly. We performed a similar mixed ANOVA analysis for the ratings of how convincing and how intense the vection in each condition was. For both of these ratings, we found a main effect of trial: for the ratings of convincingness, $F(2,20) = 11.8$, $p < 0.01$, and for the intensity ratings, $F(2,20) = 11.7$, $p < 0.01$. No other effects or interactions were significant. We explored the effect of trial on these ratings. Linear regressions were calculated to predict these variables based on trial. Significant regression equations were found for the ratings of convincingness and intensity: for the convincing rating, $F(1,238) = 9.934$, $p < 0.002$ with $R^2 = 0.04$; for the intensity rating, $F(1,238) = 7.141$, $p < 0.01$ with $R^2 = 0.03$. The mean ratings by trial are shown in Figure IV.2; the linear regression indicates that the ratings of convincingness and intensity increased 0.3 for

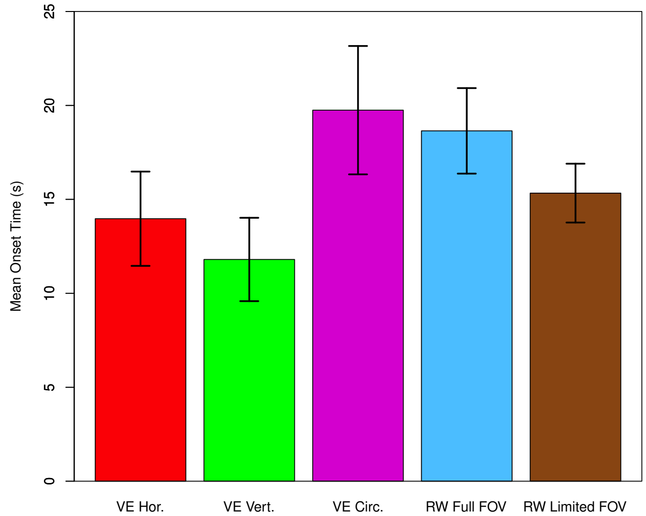


Figure IV.1: Mean reported time for onset of vection in experiment across conditions. Error bars show standard errors of the mean.

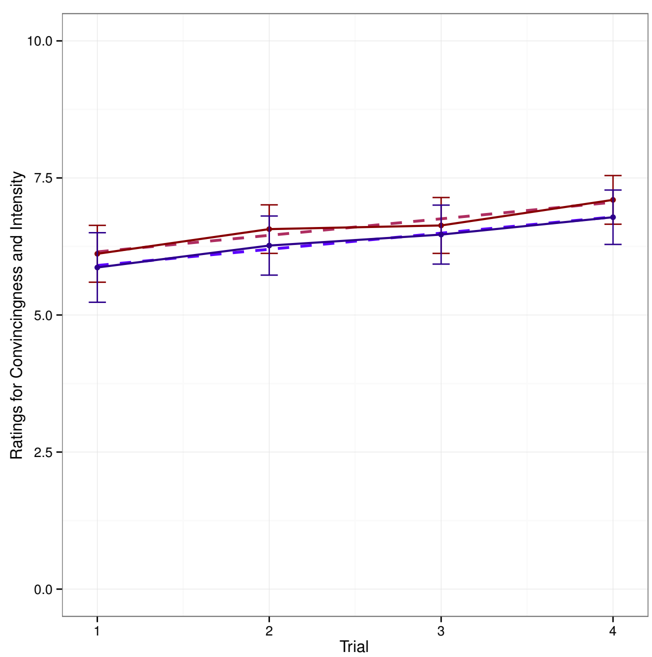


Figure IV.2: Mean ratings for the convincingness and intensity of the vection experience by experimental trial in experiment. Each subject was exposed to each condition four times (a trial). The red lines show the convincing rating (dashed is least-squares fit), and the blue lines show the intensity ratings (dashed is least-square fit). Error bars show standard errors of the mean.

each trial of vection experienced.

Participants in this experiment report reasonably convincing and intense vection. The onset latencies are quite interesting. Other researchers using similar real-world stimulus have reported circular onset latencies of 3-4s (Brandt et al., 1973). Berthoz et al. (1975) report linear vection onset latencies of 10-20s. Using a large-screen display and with a complex virtual environment, Trutoiu et al. (2009) reported linear horizontal vection of 11-13s and circular vection onset latencies of about 7s. The actual values are perhaps not as important as the relative comparison, given that vection is highly susceptible to variations in display factors. Our linear vection onset latencies are consistent with prior work, but our circular vection results are surprising and the opposite of what we hypothesized.

We note that the limited FOV condition with the real-world stimulus produced shorter onset latencies than the full FOV condition. This may seem counterintuitive given that larger FOV typically enhances vection (Berthoz et al., 1975; Brandt et al., 1973; Dichgans and Brandt, 1978). However, the goggles may have enabled the participants to fixate more easily, providing a stationary reference during experiments, and it is known that fixation reduces onset latencies (Fushiki et al., 2000; Becker et al., 2002).

Our onset latencies are roughly consistent with those of Riecke and colleagues (Riecke et al., 2015; Riecke and Jordan, 2015), who report an onset latency of 15.3s for circular vection using an NVIS SX11, and about 11s for linear vection using the same HMD as we employed, the Oculus Rift DK1. It is anecdotally believed that linear vection is more difficult to induce than circular vection (Thompson et al., 2011), and while the preceding body of work tends to support that for real-world stimuli, our experience with head-mounted displays is the opposite. We also find that the qualitative perception of vection tends to increase with exposure. This finding is interesting as Riecke et al. (2015) have found that these ratings were negatively correlated with gaming experience.

CHAPTER V

Conclusion

The purpose of this study is to effectively simulate vection based on Oculus Rift DK1 in the VR and evaluate vection based on subjective questionnaires, compared to vections in the real world. We had a within-subject experiment with 12 participants (six men and six women). Each participant experienced three virtual stimulus environments (virtual circular, virtual horizontal and virtual vertical) and two real-world stimulus environments (full FOV and limited FOV). However, not all of our results could support hypotheses mentioned before. We found that onset latency for limited FOV real-world stimulus was significantly shorter than that for full FOV real-world. Meanwhile, virtual linear vection was easier to induce than virtual circular vection. There was no obvious evidence to demonstrate that virtual linear stimulus could induce a more intensive and convincing vection than virtual circluar stimulus. But Trutoiu et al. (2009) suggested that linear vection was less convincing than circular vection in a panoramic projection. We did find that onset latency for real-world circular stimulus was significantly shorter than that for virtual circular stimulus.

A future interesting aspect of this vection study would compare vection in the abstract scenes and naturalistic scenes. The models employed in this project were based on abstract flow optics, i.e. black-white stripes. However, it is really exciting to see some complex naturalistic stimulus instead in the virtual environment. Unlike abstract stimulus, naturalist stimulus could provide a more believable and reliable sensation of involvement in VR. My lab colleague, Divine Maloney, simulated an in-house model of city instead of black-white stripes based on Oculus Rift DK2 further, in order to see whether compelling vection could be comparably induced when the stimuli are complex naturalistic scenes rather than abstract optic flow patterns. In his study, vection onset latencies with a different Oculus Rift and naturalistic scenes were quite consistent with onset latencies in this study. However, he suggested that men had a significantly lower convincing ratings than women, which we did not find in this study. One reasonable explanation in his finding could be a correlation with experience or gaming on gender difference (Riecke et al., 2015).

Vection simulation could be incorporated into other VR systems, probably improving user experience in VR. Several methods are able to make subjects explore large-tracked space while walking in a limited real-world space, including redirected walking and resetting (Williams et al., 2006, 2007; Hodgson and Bachmann, 2013). Unfortunately, those technologies still require subjects to wear expensive motion-tracking systems. Exploring VR with full physical motions in the real world needs a large amount of markers and cameras to track positions and orientations, especially in the large-tracked space. However, vection, a low-cost way in the interferences and transformations, has been suggested to facilitate spatial orientations (Riecke et al., 2012), relaxing the need to have full physical motions in VR. We believe that the potential for combination of redirected walking system and vection could be an interesting field and useful to enhance user experience in VR.

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