VECTION INDUCED BY SMALL FIELD-OF-VIEW VISUAL MOTION

by

DIZMEN, Coskun

A Thesis Submitted to

The Hong Kong University of Science and Technology

in Partial Fulfillment of the Requirements for

the Degree of Doctor of Philosophy

in Industrial Engineering and Logistics Management

July 2016, Hong Kong

Authorization

I hereby declare that I am the sole author of the thesis.

I authorize the Hong Kong University of Science and Technology to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize the Hong Kong University of Science and Technology to reproduce the thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

DIZMEN, Coskun

25 July 2016

Vection Induced by Small Field-of-View Visual Motion

by

DIZMEN, Coskun

This is to certify that I have examined the above PhD thesis

and have found that it is complete and satisfactory in all respects,

and that any and all revisions required by

the thesis examination committee have been made.

____

Professor Richard H. Y. So (Supervisor)

____

Professor Guillermo GALLEGO (Department Head)

Department of Industrial Engineering and Logistics Management

25 July 2016

Acknowledgments

The first person that I have to present my gratitude and thankfulness is my thesis supervisor Professor Richard So. He not only guided me throughout the experiments and my research, but also enlightened me with the courses he taught. Thank you very much for being my teacher and PhD supervisor. This thesis couldn’t be written without you!

I also would like to express my thankfulness to the other members of my thesis supervisory committee: Prof Jelte E. Bos, Prof Bertram Shi, Prof Xiangtong Qi, Prof Michael Wong, Prof Jiheng Zhang, and Prof Fugee Tsung. Thank you very much for your valuable time, comments, and suggestions.

I should also thank Prof. Ravindra Goonetilleke for his contributions to my research with his comments in Advanced Seminars.

I am also grateful to the lab technicians who supported me to setup my experiments: Mr Tin, Mr Denil, Mr Charles, and Mr Yung; as well as the secretaries of our department who helped me with my paperwork: Ms Fona, and Ms Vera.

A special thank has to be sent to my whole family for supporting me whatever problem I encounter throughout my PhD life, and indeed throughout my entire life.

Last but not least, I have to thank my subjects and lab mates. They are the hidden heroes of my experiments and thesis. Thank you all!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Vection Induced by Small Field-of-View Visual Motion

by DIZMEN, Coskun

Department of Industrial Engineering and Logistics Management

The Hong Kong University of Science and Technology

Abstract

Vection (illusion of self-motion) can be induced by stimulating a small portion of retina. However, a review of literature shows that most of the studies on vection utilized large field-of-views (FOVs) to induce vection. In this thesis, the minimal FOV conditions that can induce compelling vection have been investigated through a series of experiments.

Results of our experiments showed that vection can be induced with two narrow stripes (1 degree by 5 degree area) of moving dots. The other findings of our experiments on narrow/small FOVs include: (i) keeping ceiling light off induces more compelling vection compared to keeping it on; (ii) higher speed of stimuli is associated with more compelling vection within the speed limits of this study; (iii) frontal occultation by means of a cardboard induces more compelling vection compared to staring at an LED with open view; (iv) linear vection is more compelling compared to circular vection with our stimuli; (v) there is no significant difference between the vection measures of the two narrow stripes of dots moving approximately 140 degrees horizontally apart to 90, and 60 degrees apart in the front; and (vi) peripheral vision is more sensitive to vection information compared to central vision. All of these findings are tested; and their claims are found to be statistically significant.

Based on the results of our early experiments, a theory (referred to as ‘the Connection Theory’) was proposed in order to explain vection behavior at narrow/small FOVs. Later experiments of this thesis provide more exploration and evidence to support and revise the Connection Theory. This theory attempts to explain why and how small FOV visual motion induces vection by investigating the cognitive relationship between viewers and the environments surrounding them.

CHAPTER 1: INTRODUCTION

1.1. Vection

Vection is the visual illusion of self-motion of a stationary person due to an optic flow. A classic example of vection is that a stationary passenger sitting in a stationary train perceives self-motion when he/she looks at a train in the other track that starts moving.

The vection concept may be as old as our ancestors who might feel self-motion while looking at moving clouds or a flowing river (Dichgans and Brandt, 1978; Riecke, 2010). In today's world, human being encounters the vection concept frequently as vection is not only caused by motion of a physical object, but also can be induced by an optic flow in a computer monitor or movie theater screen.

An optic flow that causes vection is likely to generate symptoms of motions sickness (Hettinger et al., 1990; Ji et al., 2009; Lo and So, 2001); although the exact nature of the relationship between vection and visually induced motion sickness (VIMS) is not totally understood yet (Keshavarz et al., 2015).

Foremost symptoms of motion sickness include nausea, vomiting, stomach awareness, sweating, fatigue, disorientation, and dizziness (Kennedy et al., 2010; So et al., 1999). If a person experiences these or other symptoms of motion sickness when observing an optic flow, he/she is susceptible to VIMS. Depending on the nature of the optic flow, design components, and the context, VIMS can be categorized as cyber-sickness, gaming sickness, cinema sickness, or simulator sickness (Keshavarz et al., 2015; So and Ujike, 2010).

Vection studies carry not only scientific but also commercial value to the humankind. With the increasing popularization of 3-D movies, importance of vection studies became more prominent (Bos et al., 2013). Vection studies are also important for computer games (Guo et al., 2013), flight simulators (Hettinger at al., 1990), and any other kind of virtual reality systems (Kennedy et al., 2010).

1.2. Self-motion and vection as a term

1.2.1. What is self-motion?

A wide variety of terms have been used to describe the self-motion related concepts by different researchers, some of whom do not agree with others' usage (Owen, 1990). Warren (1990, page 7) defines the term "egomotion" or "self-motion" as "displacement of a perceiver with respect to the environment"; and keeps the word "locomotion" peculiar to movement of body parts (i.e. wing, leg, etc.) in order to make a displacement but without requiring to achieve this goal. According to this definition, a bird flapping its wings toward a strong wind has locomotion but not necessarily have self-motion if the wind doesn't allow the bird to displace.

Similar to Warren (1990), Johansson (1977) also differentiates a motion caused by the observer itself and a motion caused by outside factors. However, he uses different terminology to make this discrimination. According to Johansson (1977), if the displacement is brought by moving muscles, it is called "active locomotion" (for example, walking); if the displacement is brought by movement of a vehicle, it is called "passive locomotion" (for example, sitting in a moving bus).

In this thesis, the term "self-motion" in used to refer the displacement of a body with respect to a reference point (e.g. earth unless otherwise is mentioned); and it is sometimes preceded by the word "active" (for example, flying by flapping the wings) or "passive" (for example, sitting in a flying airplane).

1.2.2. Perception of self-motion versus object motion

Human being receives inputs about self-motion from the following three channels: visual, somatosensory, and vestibular system (Keshavarz et al., 2015). In the case of passive linear body movement by a vehicle with a constant speed, the only decision criteria for a human to detect motion is visual because such passive movement does not provide somatosensory stimulation and vestibular system is incapable of detecting a motion with a constant speed (i.e. without acceleration) (Johansson, 1977; Brandt et al., 1998).

When a human moves in an environment; the location of his/her retina that is stimulated by an object changes as the relative position of the object changes with respect to his/her eyes. Moreover, when an object gets closer or further to his/her eyes; the area that it occupies in his/her retina increases or decreases respectively. These visual cues play an important role in decision of self-motion. Therefore, if a stationary person is exposed to an optic flow that he/she expects to encounter while he/she is moving, he/she may perceive self-motion. This phenomenon is called vection.

1.2.3. Definition of vection

Palmisano et al. (2015) discusses 4 different definitions of vection (i.e. Definition #1: “A visual illusion of self-motion in a stationary observer”, Definition #2: “An illusion of self-motion”, Definition #3: “A visually mediated perception of self-motion (real or illusory)”, Definition #4: “A conscious subjective experience of self-motion (real or illusory)”). (Palmisano et al., 2015)

Some of the definitions of Palmisano et al. (2015) (i.e. definition #2, definition #4) take into account that an illusory self-motion does not have to be induced by vision. It can be induced by vestibular, auditory, biomechanical, or haptic stimuli as well because of etymologic reasons (that is “*vectio*” means “*to carry*” in Latin). More interestingly, some of the definitions he argued (i.e. definition #2 and #4) claims that vection does not even have to be illusory. To cut the long story short, in this thesis, we will follow the majority of the literature and use the definition #1 that is “a visual illusion of self-motion in a stationary observer”. (Palmisano et al., 2015)

A further reading reference about self-motion related terminology can be found in the lexicon of terms compiled by Owen (1990).

1.2.4. Definition of field of view (FOV)

Gibson (1979, pages 111-115) defines field of view as "the solid angle of the ambient light that can be registered by its ocular system". By creation, natural field of view of a human is bounded by his/her eye socket, eyelid, and sometimes nose, and other organs. Gibson's definition puts the emphasis on the observer. However, in the virtual reality literature, the term field of view is used as "the solid angle of the ambient light that is presented by the virtual environment" (Wolpert, 1990; Trutoiu et al., 2009; Duh et al., 2001; Lin et al., 2002). Following the vection studies literature, the later definition will be used in this thesis.

As the definition of FOV suggests, it is a solid angle that is a two-dimensional angle in the three-dimensional space. SI unit of solid angle is steradian. However, in vection studies, the unit of FOV is usually reported as degree-square instead of steradian.

1.3. Vection-FOV relation

Human beings can observe approximately 200 degrees horizontal and 135 degrees vertical FOV in binocular vision (Spector, 1990). However, a study of Brandt et al. (1973) discovered that vection perception does not require stimulation of the entire FOV. Their study concludes that a stimulus presented to the entire FOV of subjects induces almost same level of vection when the central vision of the subjects is blocked with a black disk of 120 degree diameter. After this discovery, many other researches have been conducted with FOVs that do not cover the entire vision although it covers most of the vision (e.g. Brandt et al., 1998; Allison et al., 1999).

In most of the virtual reality systems, covering the entire vision can be costly. Therefore, many of the head mounted displays (HMD) provide less than 50 degree FOV (Knapp and Loomis, 2004; So et al., 2001).

It is interesting to research the narrow FOV conditions that can still induce compelling vection. There have been a small number of studies on the effect of FOV on vection perception and vection-related concepts (Allison et al., 1999; Duh et al., 2001; Lin et al. 2002; see Literature Review chapter of this thesis for more details). The FOV that those studies employed ranges from 47 degree-square (or 78.54 degree-square) to full field. To the best of our knowledge, there is only one study, conducted by Johansson (1977), that investigated vection at a FOV as small as 1 degree by 47 degree.

Johansson's study (1977), discovered that more than half of his subjects, under certain conditions, reported vection at such a small FOV. However, that study may have some biases because subjects were exposed to larger FOVs first, and then the FOV was reduced gradually (till 1 degree) for the subjects who reported vection. Moreover, that study still has more room to improve. For example, Johansson (1977) has not analyzed the other factors, such as the speed of the stimuli and the ceiling light, that may affect the results. Therefore, the topic of liminal FOV for vection has not been clarified yet. In this thesis, this research gap was attempted to be filled in.

1.4. Thesis organization

Chapter 1 introduces a basic background about vection and FOV (field of view).

Chapter 2 reviews a number of researches conducted in vection and FOV.

Chapter 3 presents the methodology, results, and discussions of Experiment 1 and 2 that are conducted to investigate vection sensation when subjects are exposed to two stripes of moving dot patterns with narrow field-of-view (FOV) (1 degree by 47 degrees). This chapter analyzes the effects of ceiling light, frontal occultation, stimuli direction, and stimuli speed on vection perception.

Chapter 4 presents the methodology, results, and discussions of Experiment 3 that is conducted to investigate effects of vection type (i.e. circular/linear) and vertical FOV on vection perception.

This chapter attempts to explain the mechanism of vection perception via small FOVs by proposing a theory: the Connection Theory.

Chapter 5 presents the methodology, results, and discussions of Experiment 4 that is conducted to investigate effect of horizontal location on vection perception. This chapter provides further reasoning for and explanation on the Connection Theory.

Chapter 6 presents the methodology, results, and discussions of Experiment 5 that is conducted to discover the effect of closing one eye (i.e. seeing only one stimulus) after experiencing circular vection with two eyes to two stripes moving in opposite directions at peripheral vision. This chapter attempts to test validity of the Connection Theory, and explore more.

Chapter 7 presents the methodology, results, and discussions of Experiment 6 that is conducted to compare two long stripes moving in opposite directions located close to each other, with two short stripes located at the same horizontal location at the central vision (via the Connection Theory). This chapter also discusses inducing vection at central vision.

Chapter 8 summarizes the main findings of this thesis, states limitations to this thesis, and concludes with possible future work.

CHAPTER 2: LITERATURE REVIEW

2.1. Early studies and two-modes/systems theory

The first researcher who analyzed vection in laboratory experiments is Mach (Warren, 1995; Mestre, 1992). Mach set up a drum with vertical stripes inside it, and the drum was rotated while a subject is seated inside of it. Although the subject was not moving, he/she perceived self-motion in the opposite direction to the rotating drum. This type of illusory self-motion is called circular vection (CV).

Brandt et al. (1973) also used the rotating drum stimulus. According to their study, blocking the peripheral vision, a stimulus presented to the area up to 30 degree in the central vision results in perception of the object motion without inducing vection. However, a stimulus presented to the peripheral vision, blocking the central vision with a black disk of 120 degree, results in vection. Another experiment of the same study analyzed stimuli in conflicting directions, and showed that peripheral vision predominates perception of vection (i.e. exocentric motion) and central vision predominates perception of object motion (i.e. egocentric motion). Based on their experiments, they hypothesized two systems to perceive motion: peripheral system for exocentric, and central system for egocentric motion.

Leibowitz et al. (1983) defines these two visual systems as “focal mode” and “ambient mode” (sometimes labeled as focal system and ambient system (e.g. Johansson et al., 1980, page 51)). Focal mode is responsible for the question of “what”, i.e. what is the shape or pattern of the object; while ambient mode is responsible for the question of “where”, i.e. where is it at or moving. Peripheral vision is more effective in ambient mode, whereas central vision is more effective in focal mode. Focal vision requires attention of the observer and is good at detecting local changes, while ambient vision can work without a great deal of attention and is good at detecting global changes. Due to their nature, focal system is associated with perception of object motion, and ambient mode is associated with perception of self-motion. (Johansson et al., 1980; Leibowitz et al., 1983)

Although the above theory is quite reasonable and valid with its supportive experiments, one should always keep in mind that vection perception can be affected by the observer's expectation to have a real motion, and the context (Riecke, 2009). Therefore, it is possible to find a stimulus that can generate stronger vection at the central vision compared to the peripheral vision (e.g., Wolpert, 1990).

2.2. Studies on small FOV

In this section, a number of research studies on the effect of FOV on vection, balance, simulator sickness, presence, memory, heading directions, and visual tracking task performance have been reviewed. Their major findings have been reported briefly, including the FOV range that they used.

2.2.1. Allison, Howard, and Zacher (1999)

In vection studies, it is common to encounter computer-generated stimuli. However, Allison et al. (1999) used a physical cubic room of size 2.1 x 2.1 x 2.1 m in their study. They named it "tumbling room" because it can rotate in the roll axis for 360 degree. The subject sat on a stationary chair located in the tumbling room and observed the rotation of the room through 5 different field-of-views: 20, 50, 80, 100 degree, and full field. For the full-field condition, 80% of their subjects experienced 360degree illusory full rotation. However, this number dropped to 31% for the 20 degree FOV condition. They also noted that quality of the illusion changes when the FOV increases, reaching the most compelling level at the full-field.

Personal judgment about the gravity vector is made using the following three cues: “visual frame” (e.g. walls and ceiling of a room may construct a visual frame), “visual polarity” (e.g. a human has intrinsic visual polarity as has head at the top and feet at the bottom), and “motion of visual scene”. Reducing the FOV, reduces the available cues reaching subject’s eye. Therefore, fewer subjects reported 360degree illusory full rotation in the small FOVs.

2.2.2. Duh, Lin, Kenyon, Parker, and Furness (2001)

Using two types of virtual scenes (a city scene, and a radial pattern), Duh et al. (2001) tested six different FOVs (30, 60, 90, 120, 150, 180 degree). The visual scene was oscillated in roll axis with 0.05 Hz frequency, and balance disturbance of subject was the topic of interest. They investigated balance because it can predict simulator sickness, and it does not have undesirable aftereffects on subjects who attended the experiment. They discovered that balance disturbance increases with increasing FOV for both city scene and the radial pattern.

Duh and colleagues also co-authored another study with a virtual environment of different FOVs (60, 100, 140, 180 degree). That study proposed that simulator sickness, presence, and memory task scores increases with the increasing FOV. (Lin et al., 2002)

2.2.3. Other researches on FOV in a nutshell

Table 2.1 includes summary of several studies on the effect of FOV on vection, balance, simulator sickness, heading directions, visual tracking task performance.

Table 2.1 Summary of literature on the effect of FOV on vection related concepts

Trutoiu et al. (2009)	Title of the study	Circular, linear, and curvilinear vection in a large-screen virtual environment with floor projection
	FOV type and size	Spherical: 220x165 (with and without floor projection)
	Minimum FOV tested	36300 degree-square
	Stimuli content	3D virtual environment simulating the city of Tubingen
	Major finding	Addition of the floor projection increases linear vection whereas does not affect circular vection
Bos et al. (2010)	Title of the study	The effect of internal and external fields of view on visually induced motion sickness
	FOV type and size	ExternalFOV (i.e. DisplayFOV): Rectangular: 40x40, 103x103; InternalFOV (i.e. CameraFOV): Rectangular: 30x30, 60x60
	Minimum FOV tested	1600 degree-square
	Stimuli content	"Open coastal environments and more up-close city areas"

	Major finding	Larger display FOV causes higher misery ratings. CameraFOV(i.e.InternalFOV) doesn't have significant effect on misery ratings.
Harvey and Howarth (2007)	Title of the study	The Effect of Display Size on Visually-Induced Motion Sickness (VIMS) and Skin Temperature
	FOV type and size	Rectangular: 27x21, 48x36, 62x47 degree
	Minimum FOV tested	567 degree-square
	Stimuli content	A computer game named "Killer Loop"
	Major finding	VIMS ratings increases with increasin FOV
Duh et al. (2001)	Title of the study	Effects of Field of View on Balance in an Immersive Environment
	FOV type and size	Circular: Radius of 30, 60, 90, 120, 150, 180 degree
	Minimum FOV tested	706.86 degree-square

	Stimuli content	Two visual scenes (city scene and radial pattern) oscillated in roll axis
	Major finding	Balance disturbance increases with increasing FOV
Allison et al. (1999)	Title of the study	Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room
	FOV type and size	Circular: Radius of 20, 50, 80, 100, 360 (full field)
	Minimum FOV tested	314.16 degree-square
	Stimuli content	A physical cubic room that can rotate in roll axis
	Major finding	Number of subjects who reported 360 degree full rotation increases with increasing FOV
Kenyon and Kneller (1993)	Title of the study	The Effects of Field of View Size on the Control of Roll Motion
	FOV type and size	Circular: 10, 20, 40, 80, 120 degree
	Minimum FOV tested	78.54 degree-square

	Stimuli content	Visual tracking task
	Major finding	Subjects reported increased task difficulty at the widest FOV (i.e. 120 degree) because perception of vection interfered their performance
Warren and Kurtz (1992)	Title of the study	The role of central and peripheral vision in perceiving the direction of self-motion
	FOV type and size	Circular: 10, 25 (diameter); Rectangular: 40(horizontal)x32(vertical), Peripheral: The central vision of rectangular area was blocked till 15 degree diameter
	Minimum FOV tested	78.54 degree-square
	Stimuli content	3D cloud of dots
	Major finding	Vection can be induced in the central vision with a 10 degree circular area with a 3D cloud of dots. Central vision is good at extracting radial, rotary, and lamellar flow, while peripheral vision is only good at lamellar but not at radial or rotary flow.
Stern et al. (1990)	Title of the study	The effects of fixation and restricted visual field on vection-induced motion sickness
	FOV type	Full field / Circular: Radius of 15 degree

	and size	
	Minimum FOV tested	176.71 degree-square
	Stimuli content	Rotating drum
	Major finding	Viewing the rotating drum through a 15 degree FOV induces much less vection compared to full field. Fixating eyes induces less vection compared to free eyes.
Johansson (1977)	Title of the study	Studies on visual perception of locomotion
	FOV type and size	Rectangular: 1x47, 10x47, 45x47 degree
	Minimum FOV tested	47 degree-square (this is the FOV observed by each eye. However, the total FOV of the entire stimuli is double of this size i.e. 94 degree-square.)
	Stimuli content	Falling / rising dots
	Major finding	Vection can be induced at a stripe of 1degree horizontal by about 47 degree vertical FOV. Peripheral vision is more sensitive to this stimulus.

2.3. Johansson (1977)

Johansson reported a study in 1977 about two experiments he conducted on vection (see Johansson, 1977). His first experiment compared the roles of peripheral and central vision in vection perception. Being parallel to the results of Brandt et al. (1973), Johansson's result showed no vection at central vision (covering the central 30 degree), whereas compelling vection at peripheral vision (covering a band from 45 to 90 degree of each eye).

In his second experiment, Johansson (1977) investigated the area of peripheral vision that is more sensitive to vection. He used 10-degree horizontal bands covering 55-65, 60-70, and 80-90 degree. He concluded "there hardly is any difference in the mean latencies" of these 10-degree-bands. The reason he provided is "inter-individual variability". Although he discussed the mean vection onset times, he didn't discuss about exact variation among the subjects. Therefore, we are unable to judge if the difference is significant or just by chance. Thus, the topic of the peripheral area that is more sensitive to this type of stimulus is not clarified in his study.

In the second phase of his second experiment, Johansson (1977) analyzed the liminal horizontal FOV that can induce vection. He picked up the band covering 60-70 degree in horizontal for investigation. First, he presented the stimuli at the 10 degree band to the subject until he/she reported vection or 2 minutes passed. If the subject reported vection, the FOV was reduced to 9 degree and experiment was repeated. As long as the subject reported vection, the horizontal FOV was reduced in the steps of 1 degree until the 1-degree-liminal-FOV was reached. 12 out of 15 subjects reported vection at 1 degree horizontal FOV. However, this procedure may have bias because a subject who reported vection at 10 degree FOV may be conditioned to report vection at a very similar width of 9 degree FOV.

Addition to that bias, Johansson's study (1977) didn't include a subjective rating about the personal experience of the subjects. He used vection onset times as the only criteria to judge vection. However, vection onset time does not have to be always correlated with subjective rating (as it will be discussed later in this thesis).

It is a fact that Johansson's study (1977) provides a very good supportive proof for some issues on vection (see Brandt et al., 1973). However, for the truth of "vection at narrow FOVs", it only gives us a blurry glimpse. In order to clarify the issue of vection at narrow FOVs, we identified the research gaps (see Section 2.4 of this thesis) and conducted a series of experiments to fill in those gaps.

2.4. Our motivation to focus on Johansson's study

If we consider about the FOV observed by each eye of the subject, the smallest FOV area that has been tested by other researchers is 47 degree-square (Johansson, 1977). Therefore, we wanted to focus on Johansson's study although his stimuli area becomes 94 degree-square if we consider about the total area of the stimuli because there were two monitors at each side of the subject in his study. Johansson's stimuli is random dot pattern on a narrow stripe which can be adopted into may other applications and manipulated easily as well. That's why we focused on his study in this thesis.

This paper of Johansson (1977) has been cited more than 200 times in the literature. For example, Trutoiu et al. (2009) mentioned that Johansson achieved to induce vection at horizontal FOV of 1 degree although Trutoiu et al. (2009) themselves used a FOV of 200 degree horizontal by 165 degree vertical to analyze the effect of vection type on vection strength. The other researchers who cited Johansson's (1977) paper also generally mentioned about the possibility of achieving vection at such small FOVs while their focus was not small FOVs. For example, Bertenthal (1993) focused on perception of motion in infants; Knight and Johnston (1997) focused on movement and face recognition; Rocchesso and Fontana (2003) focused on relation of hearing and movement perception; Lee et al. (1992) focused on balance of somersaulters; Howard (2012) focused on how depth is perceived. However, none of them has focused on vection at a FOV as small as 1 degree in horizontal as Johansson did. Therefore, Johansson's paper (1977) still needs special attention; and we attempted to pay it throughout this thesis.

2.5. Research gaps

Research Gap 1: The effects of ceiling light, direction of stimuli, and speed of the stimuli on vection at narrow FOVs have not been analyzed yet.

Research Gap 2: Although the liminal FOV in horizontal axis has been analyzed, that in vertical axis has not been analyzed.

Research Gap 3: The effect of location of the narrow FOV within the visual field has not been analyzed yet.

Research Gap 4: As far as we know, there is no study on liminal FOV concerning the circular vection through two linear stripes.

In this thesis, we aimed to fill in these gaps with a series of experiments.

2.6. Hypotheses of this thesis

H1: If we eliminate the bias, two stripes of moving dots viewed through 1x47-degree-FOV do not cause vection.

H2.A: Keeping ceiling light off causes more compelling vection than keeping ceiling light on.

H2.B: Vection measures when ceiling light is off and on are similar after eye adaptation to dark/light.

H3: Frontal occultation causes more compelling vection compared to open view with staring at an LED. (Johansson, 1977)

H4: Stimuli direction does not affect vection measures. (Allison et al., 1999)

H5: Stimuli speed affects vection measures. (Allison et al., 1999) (Contradicts to: Johansson, 1977)

H6: Smaller FOV causes less compelling vection compared to larger FOV. (Allison et al., 1999)

H7: Circular vection is more compelling compared to linear vection. (Trutoiu et al., 2009: Yaw is more compelling than fore-and-aft.)

H8: Two stripes of 1x5 degree (or 1x40 degree) stimuli located at both sides of a viewer can also cause vection at different locations of the peripheral vision other than 70 degree horizontal location.

H9: After perceiving circular vection for two stripes located at each side, closing one eye doesn't stop circular vection immediately. (See the Connection Theory.)

H10: Vection can be induced at central vision as well.

H11: Two long stripes (i.e. 1x40 degrees) going in opposite directions do not induce more compelling vection than two short stripes (i.e. 1x5 degrees) when they are placed very close to each other.

CHAPTER 3: EXPERIMENT 1 & EXPERIMENT 2: EFFECTS OF SPEEDS, MOTION DIRECTIONS, FRONTAL OCCULTATION AND DARK ADAPTATION ON VECTION PERCEPTION WITH NARROW VISUAL MOTION

3.1. Introduction

Johansson (1977) reported that vection can be achieved at field of views (FOVs) as narrow as 1 degree horizontal by approximately 47 degree vertical. A review of literature indicates that although vection has been the subject of many studies, most studies used visual stimuli with wider FOV (Table 2.1).

In Johansson's study, all subjects were first exposed to the stimulus in a larger FOV (10 degree in horizontal x 47 degree in vertical) and the FOV was systematically reduced to one degree horizontal (by 47 degree vertical) or until vection was no longer reported. This procedure may cause a bias towards vection enhancement. Therefore, we have conducted a series of experiments to see if such a small FOV can cause vection after we eliminate the bias (Hypothesis 1). Moreover, our study provides more insights because Johansson used vection onset time as the only criteria for the measure of vection; and the strength of vection was not measured by Johansson.

An initial pilot experiment showed that it is possible to cause vection at 1x47 degree FOV even after eliminating the bias. Therefore, we designed Experiment 1 to test what factors affect vection perception at such FOV. The factors tested in Experiment 1 are (i) presence and absence of ceiling light, (ii) with and without frontal occultation: holding a cardboard to block frontal vision versus staring at an LED with an open view, (iii) direction of the visual stimuli (upward/downward), and (iv) speed of the stimuli. In short, Experiment 1 can be referred to as the Preliminary-Exp. because its objective was to examine the effects of various factors and to verify whether we would be able to duplicate Johansson's results.

Johansson found that blocking the central vision by subject's own hands causes vection more compared to an open view of the experiment room. In order to standardize the experimental procedure and make it possible for further applications, we used a cardboard for blocking the central vision. The other factors of Experiment 1 (Preliminary-Exp) (i.e. effects of speed, stimuli direction, and ceiling light) were not analyzed by Johansson (1977).

In Experiment 1 (the Preliminary-Exp), all factors were randomized in order to minimize the effect of fatigue and learning effect. However, the randomized sequence inevitably involved turning the ceiling light on and off consecutively.

Human eyes take time to adapt to a dark environment (Hecht et al., 1937). In order to investigate the effect of eye adaptation to darkness and light, Experiment 2 was conducted in two separate sessions (ceiling light on and ceiling light off). Order of presenting the sessions was randomized across subjects. Because the objective of Experiment 2 was to examine the influence of dark-adaptation, Experiment 2 was also referred to as the Dark-adaptation-Exp.

3.2. Experiment 1 (the Preliminary-Exp)

3.2.1. Methods of Experiment 1 (the Preliminary-Exp)

3.2.1.1. Subjects

16 self-reported healthy subjects (12 male) were recruited into the first experiment. The age of the subjects ranged from 18 to 31 years with a mean of 24.125 and median of 23.5 years. All of the subjects were tested to have normal or corrected to normal vision according to 20/20 protocol. After the experiment procedure was introduced, all subjects gave a written consent knowing that they can withdraw anytime from the experiment upon their request.

3.2.1.2. Setup of Experiment 1 (the Preliminary-Exp.)

The experimental setup is illustrated in Figure 3.1-3.

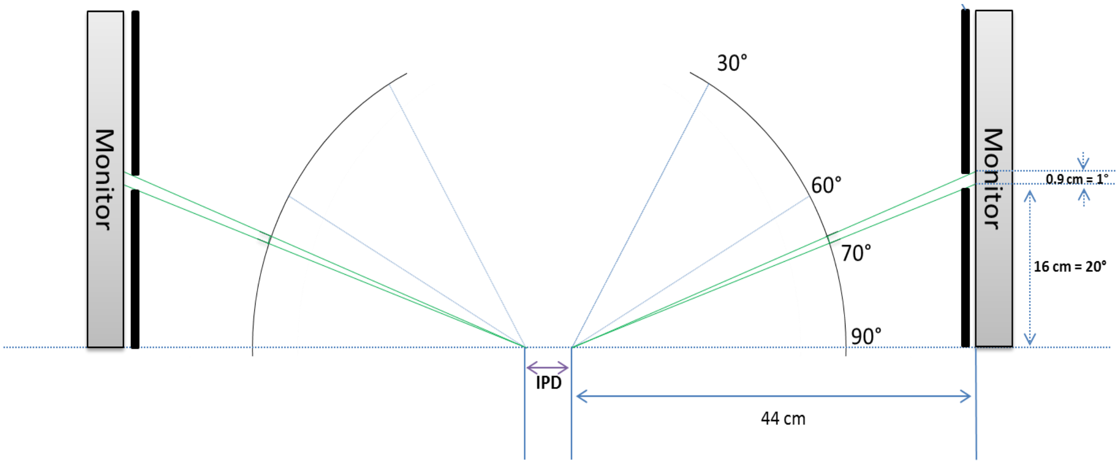

Figure 3.1: Top view of the setup of Experiment 1 and 2

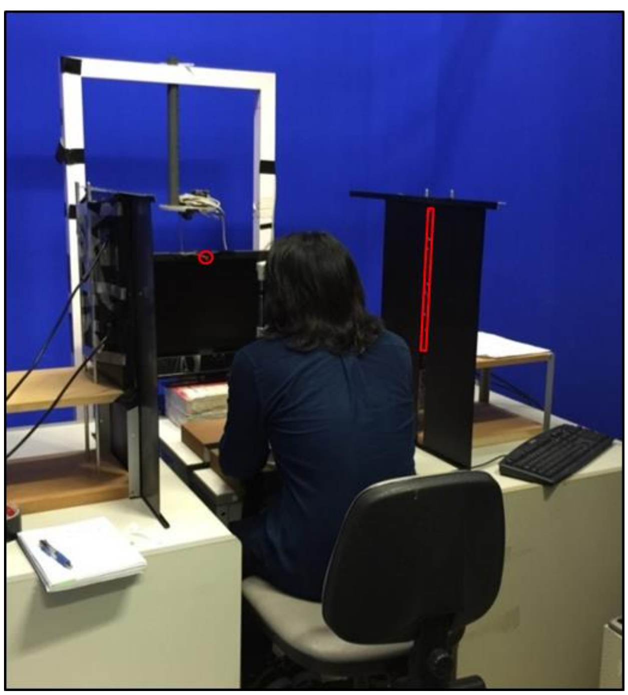

Figure 3.2: Annotated picture of setup of Experiment 1. The red rectangle on the left was added to the picture to highlight the stimuli area; and the red circle at the front of the subject was added to the picture to highlight eye fixation point.

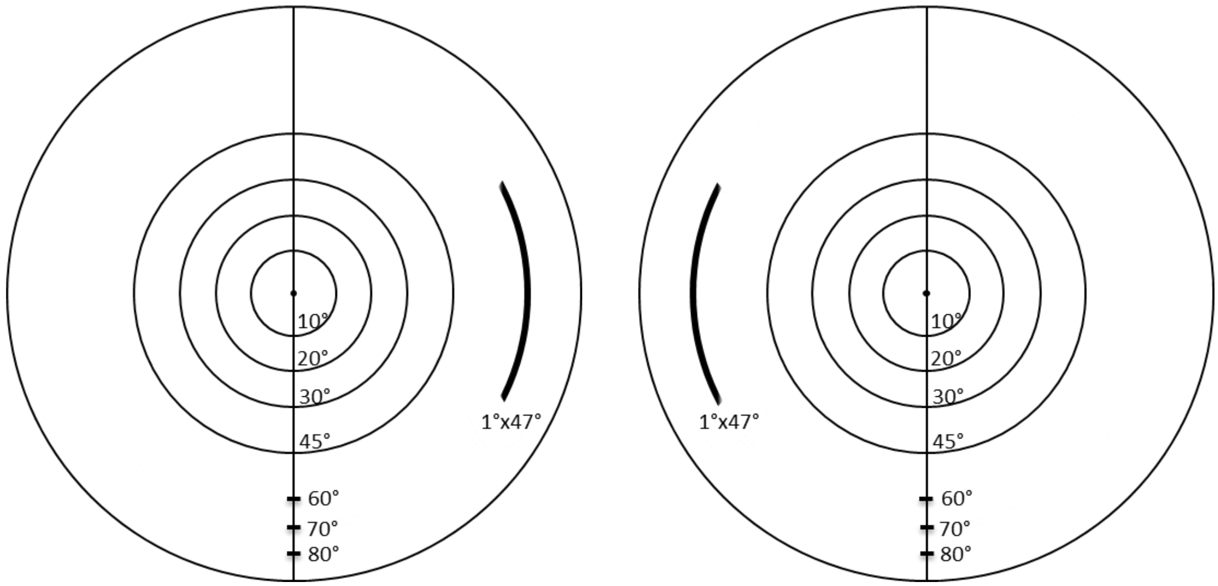

Figure 3.3: Perimetric chart of (a) left eye, (b) right eye (stimulus is on the nasal side in each figure)

In this experiment, stimuli of vertically moving white dots were displayed on a black background with two monitors on each side of the subject. The size and speed of all dots were same during each treatment with speed values of approximately 4, 8, 16, 21.4 cm/sec (corresponding to 4.6, 9.2, 18.4, 24.6 °/sec at 70° horizontal location). Each white dot was rectangular in shape and covered approximately 0.5 cm in horizontal (/width) and 0.3 cm in vertical (/height). The area of the stimuli presented on each monitor was 0.9 cm in width and 41 cm in height corresponding to a horizontal FOV of 1°, and a vertical FOV of 47°.

For displaying the stimuli, two monitors (Model ID: Philips 192E1SB/69) were used. In order to provide longer vertical FOVs, the monitors were rotated 90 degrees to sit on their narrower edges on stable platforms. With this arrangement, the visible vertical area of each monitor was set to 41 cm covering 47° vertical FOV at 70° horizontal location (Johansson, 1977) (see Figure 3.1).

The monitors were parallel to subject's sagittal plane of body. The horizontal FOV of the stimuli visible to the subject was kept constant covering horizontal FOV of 1° (from 70° to 69°) (see Figures 3.2, 3.3a,b). For determining the required horizontal distance of the monitors from each subject, the inter-pupillary distance (IPD) of each subject was also measured (see Figure 3.1).

3.2.1.2. Design and Procedure of Experiment 1 (the Preliminary Exp.)

A full factorial randomized block design was adopted using subjects as blocks. The independent factors analyzed are (i) presence and absence of ceiling light, (ii) holding a cardboard to block frontal vision versus staring at an LED placed at the front of the subject, (iii) direction of the visual stimuli (upward/downward), and (iv) speed of the stimuli (4.6, 9.2, 18.4, 24.6 °/sec at 70° horizontal location).

The strength of the vection was measured using a subjective vection rating (0 to 6: see table 3.1) and vection onset time (0 to 120 seconds).

7-Point Likert Scale for Vection Rating (adopted from Allison et al. (1999))		
Rating	**Definition**	**Explanation**
0	Only dots are moving	I feel that I am stationary, and only the dots are moving.
1	Dots' Speed >> My Speed	I feel that I am moving a bit but dots are moving much more.
2	Dots' Speed > My Speed	I feel that I am moving but dots are moving more.
3	Dots' Speed = My Speed	I feel that I am moving at the same speed as the dots.
4	Dots' Speed < My Speed	I feel that dots are moving but I am moving more.
5	Dots' Speed << My Speed	I feel that dots are moving a bit but I am moving much more.
6	Only I am moving	I feel that the dots are stationary, and only I am moving.

Table 3.1: Subjective vection rating scale (adopted from Allison et al., 1999)

The factors that are fixed at a level and not changed during the experiment are as follows: Horizontal location: 70°, Vertical FOV: 47°, Horizontal FOV: 1°

The subjects placed their heads on a chin-rest for stabilizing their heads; and the height of the chin-rest was adjusted so that the center of the stimuli matched with the subject's eye level. The main purpose of using the chin-rest in this experiment was to ensure that subjects' eyes are at the desired locations for the desired FOV values. Chin-rest gives earth-fixed location cues to the subjects which may induce longer vection onset times and lower vection ratings in our experiments.

The experiment room was rich in visual location cues such as furniture. For the staring at LED condition, the LED was located 60 cm away from subjects' eyes at about same height as their eyes. To ensure that subject was looking at the LED, their eye movements were recorded with an infrared camera. The camera recordings were not needed for the holding a cardboard condition as subjects were only asked to look inside the frame of the cardboard. The cardboard was black in color having dimensions of 35 cm x 28.5 cm. Subjects were instructed to hold it with two hands in front of their eyes and stare at the center of the cardboard (which does not have an LED) so that they can see almost nothing except for the experimental stimuli at the peripheral vision.

Before, conducting the real experiment, all subjects were exposed to the same stimuli at 10° horizontal FOV when ceiling light was off. The purpose was to educate the subjects about the feeling of vection and familiarize themselves with the procedure of reporting vection strength and onset. (Note that in future experiments, we directly showed the narrowest FOV conditions of experiments; and conducted the training at that narrow/small FOV.)

During the experiment, each subject was exposed to each combination of the factors once for utmost 120 seconds. A few seconds before each stimulus was started to be presented, subjects were verbally informed to pay attention that a stimuli would be coming soon. Subjects were instructed to report the onset and the rated level of vection strength. Once the vection was reported, the stimuli stopped. The maximum period of exposure to the stimuli was 120 seconds.

For the trials at which no vection was reported at the end of 120 seconds, the rating was recorded as 0. The analysis of rating is straightforward. However, the vection onset times for no-vection cases need a special care through two separate analyses. Analysis 1 (OnsetTime_Excluding): Discarding data points where no vection occurs. (As a paired test may not be suitable to this subset, non-paired tests are preferred for them: e.g. Mann-Whitney U Test, Kruskal-Wallis Test). Analysis 2 (OnsetTime_Including): Assuming that onset time is equal to 121 seconds, which is the smallest integer that is still bigger than the maximum possible reported-onset-time, (in order to let no-vection cases be ranked lower in nonparametric tests: e.g. Wilcoxon Signed-Rank Test, Friedman Test). In the rest of this thesis, the following notation will be followed: "OnsetTime_Including and OnsetTime_Excluding" corresponding to the two analyses mentioned here; and both of them are reported in seconds.

It has to be noted that choice of 121 seconds for OnsetTime_Including variable does not affect the non-parametric tests that are employed in this thesis. Another arbitrary number (e.g. 240 seconds) would yield the same non-parametric test results as only the ranking is important in those tests.

3.2.2. Results of Experiment 1 (the Preliminary-Exp.)

The independent variables of Experiment 1 were (i) Ceiling light (ON/OFF), (ii) Frontal occultation (Holding a cardboard / Staring at an LED), (iii) Direction of stimuli (Downward/Upward), (iv) Speed (4 levels). The dependent variables were OnsetTime_Including, OnsetTime_Excluding, and Rating. Since the assumptions of ANOVA were violated, non-parametric tests were applied; i.e. Wilcoxon signed-rank test, Mann-Whitney U Test, Friedman Test, and Kruskal-Wallis Test.

3.2.2.1. Main Effects of Ceiling Light

Compared to keeping the ceiling light ON, keeping the ceiling light OFF causes significantly shorter OnsetTime_Including (p<0.0001; Wilcoxon Signed-Rank Test), shorter OnsetTime_Excluding (p<0.0001; Mann-Whitney U Test), and significantly higher vection ratings (p<0.0001; Wilcoxon Signed-Rank Test). Shorter vection onset times and higher vection ratings are associated with more compelling vection. Therefore, keeping the ceiling light off causes significantly more compelling vection. (See Figure 3.4)

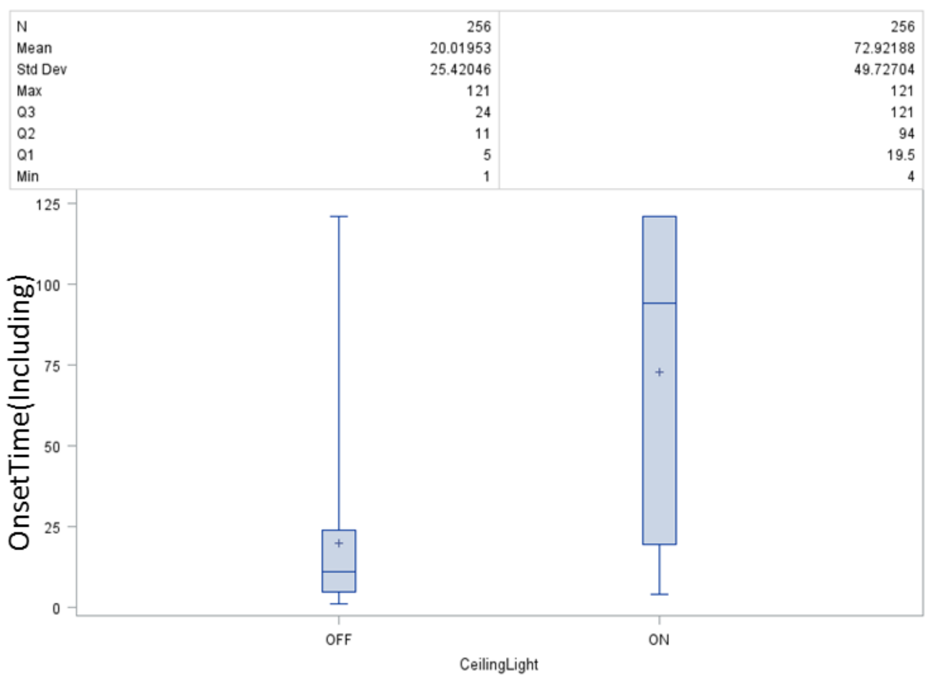

Figure 3.4.a: Main Effects of Ceiling Light in Experiment 1 on Onset time including no-vection cases

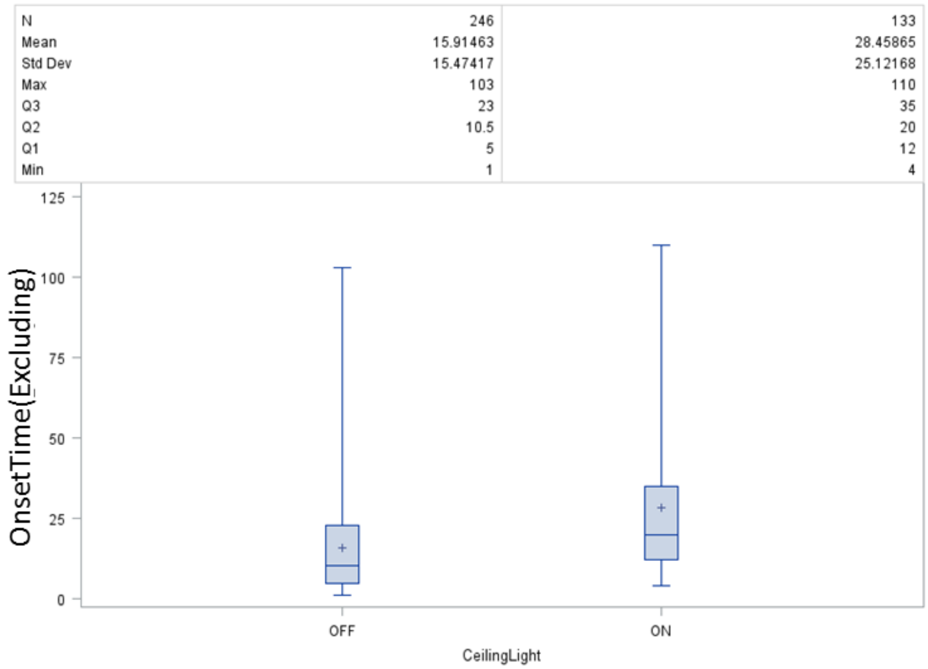

Figure 3.4.b: Main Effects of Ceiling Light in Experiment 1 on Onset time excluding no-vection cases

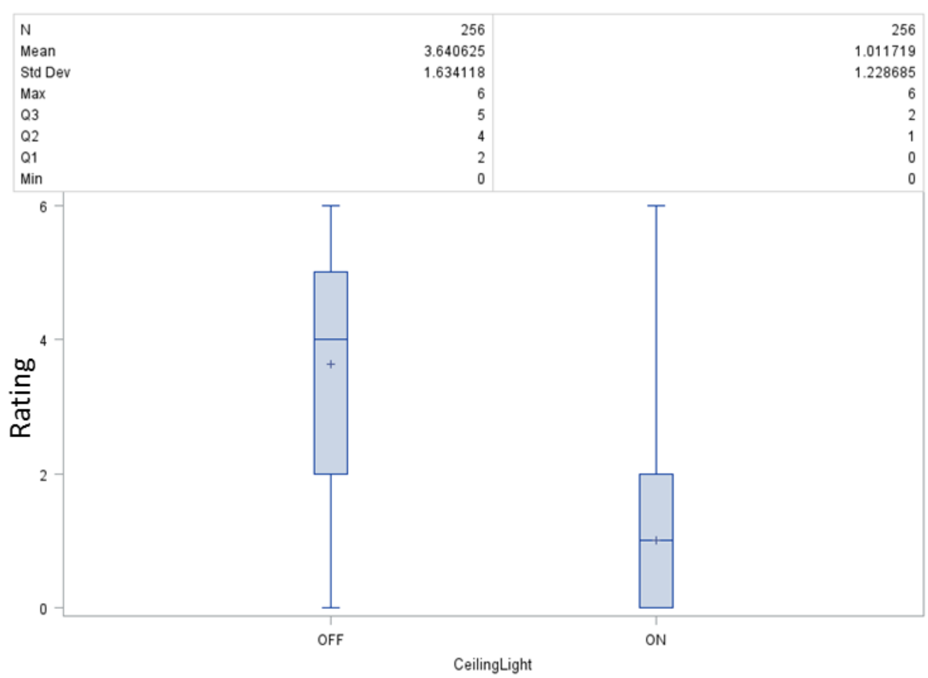

Figure 3.4.c: Main Effects of Ceiling Light in Experiment 1 on Rating

3.2.2.2. Main Effects of Frontal Occultation

Compared to staring at an LED with open view, holding a cardboard to block central vision causes significantly shorter OnsetTime_Including ($p<0.0001$; Wilcoxon Signed-Rank Test), and significantly higher vection ratings ($p<0.0001$; Wilcoxon Signed-Rank Test). However, the difference between cardboard and LED is not significant for OnsetTime_Excluding ($p>0.1$; Mann-Whitney U Test). It means that within the subset of the trails where vection occurred, the onset time of cardboard and LED are not significantly different, although cardboard causes significantly shorter onset times in the overset assuming no-vection cases have larger onset times than vection-positive cases. (See Figure 3.5)

N	204	175
Mean	19.78922	20.93143
Std Dev	17.95423	22.74208
Max	93	110
Q3	27	28
Q2	14.5	12
Q1	7	6
Min	1	2

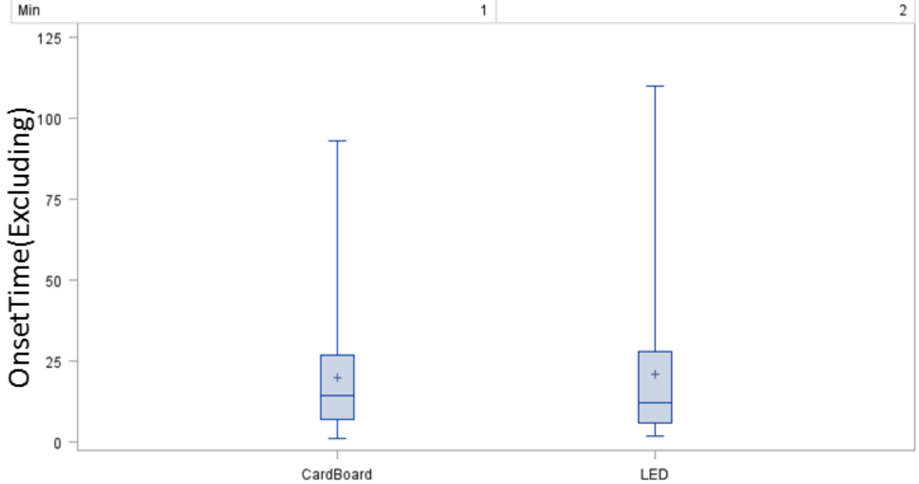

Figure 3.5.a: Main Effects of Frontal Occultation in Experiment 1 on Onset time including no-vection cases

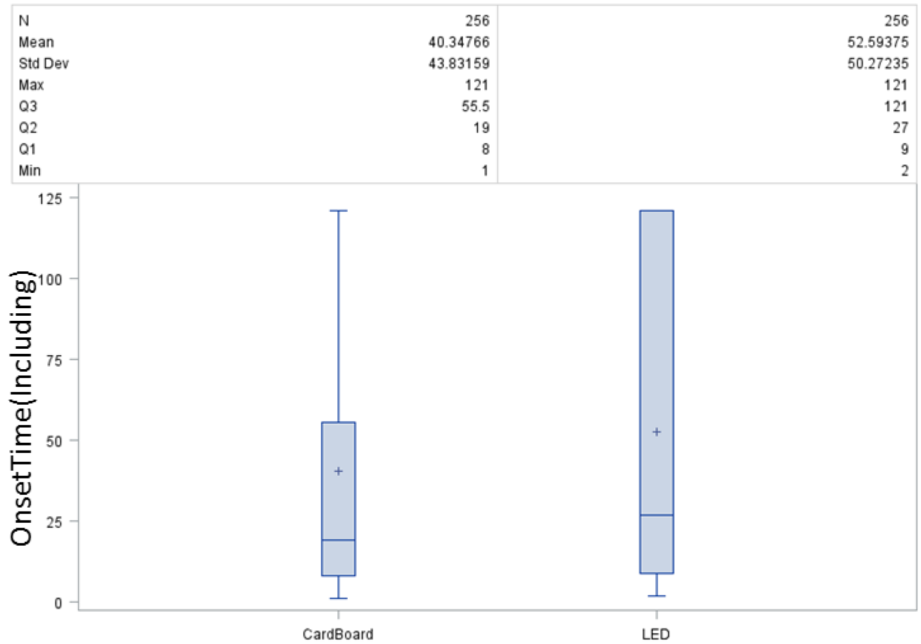

Figure 3.5.b: Main Effects of Frontal Occultation in Experiment 1 on Onset time excluding no-vection cases

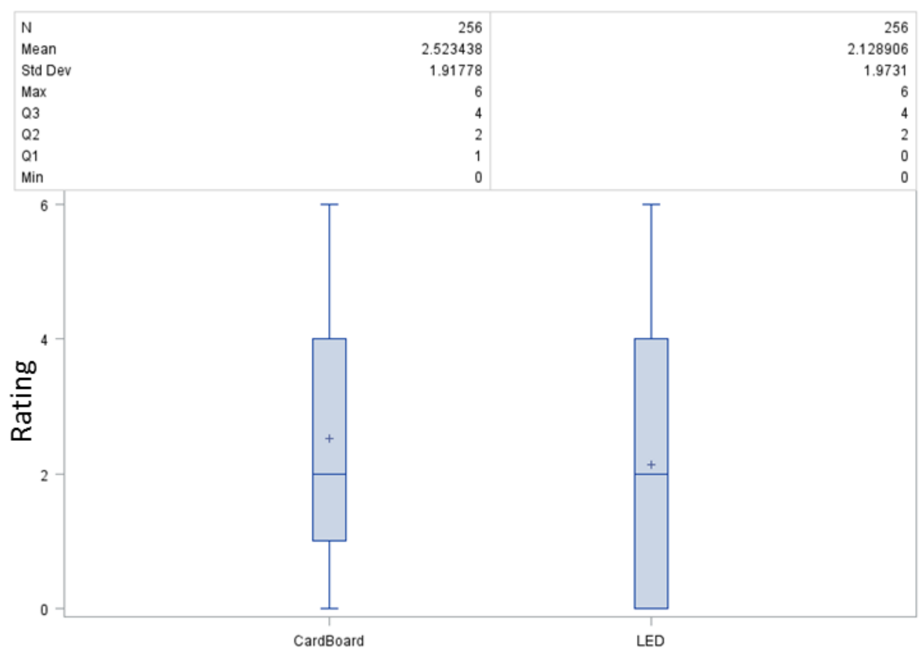

Figure 3.5.c: Main Effects of Frontal Occultation in Experiment 1 on Rating

3.2.2.3. Main Effect of Stimuli Direction

Stimuli direction does not have significant main effect on any of the vection measures i.e. OnsetTime_Including ($p>0.1$; Wilcoxon Signed-Rank Test), OnsetTime_Excluding ($p>0.1$; Mann-Whitney U Test), Rating ($p>0.1$; Wilcoxon Signed-Rank Test). Therefore, upward and downward stimuli have similar effects on vection onset times and rating. (See Figure 3.6)

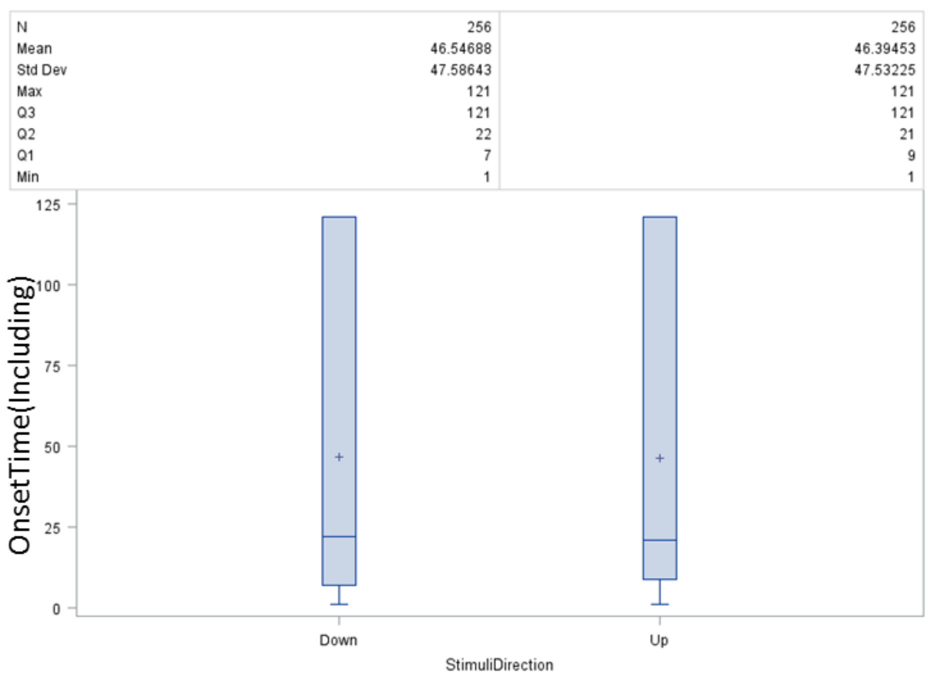

Figure 3.6.a: Main Effects of Stimuli Direction in Experiment 1 on Onset time including no-vection cases

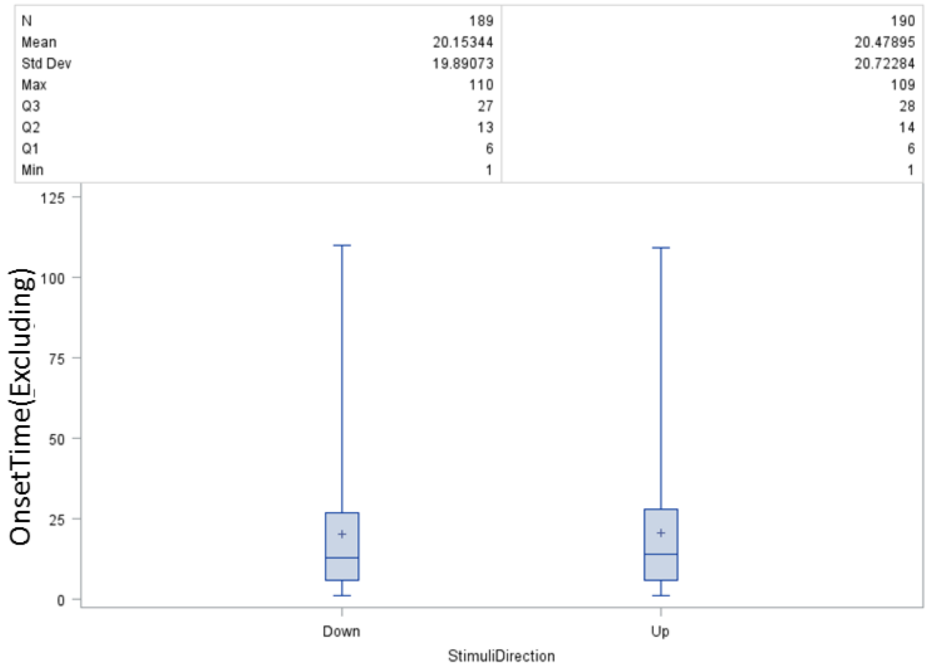

Figure 3.6.b: Main Effects of Stimuli Direction in Experiment 1 on Onset time excluding no-vection cases

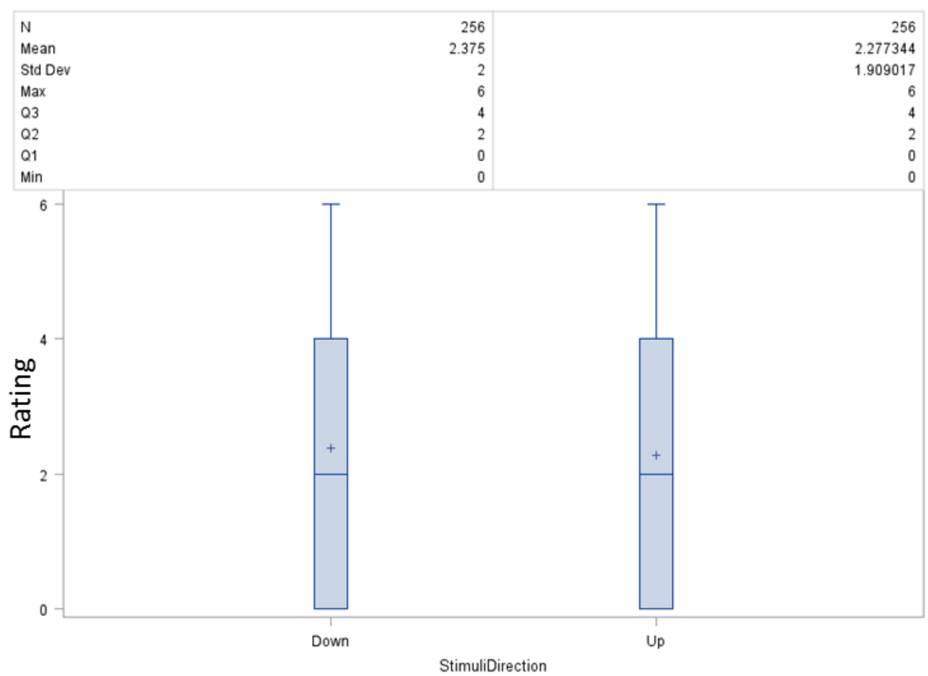

Figure 3.6.c: Main Effects of Stimuli Direction in Experiment 1 on Rating

3.2.2.4. Main Effects of Stimuli Speed

Stimuli speed affects all of the vection measures i.e. OnsetTime_Including ($p<0.0001$; Friedman Test), OnsetTime_Excluding ($p<0.05$; Kruskal-Wallis Test), Rating ($p<0.01$; Friedman Test). There is a general trend that the higher the speed (within our limits), the more compelling the vection. A post-hoc analysis with Wilcoxon Signed-Rank Test (for OnsetTime_Including and Rating) and Mann-Whitney U Test (for OnsetTime_Excluding) on each pair showed the pairs that are significantly different. (See Figure 3.7 and Table 3.2)

N	128	128	128	128
Mean	51.39063	49.00781	45.04688	40.4375
Std Dev	47.36044	48.56938	48.68667	45.17974
Max	121	121	121	121
Q3	121	121	121	55.5
Q2	31.5	24	18	18.5
Q1	11	10.5	7.5	7
Min	3	1	1	1

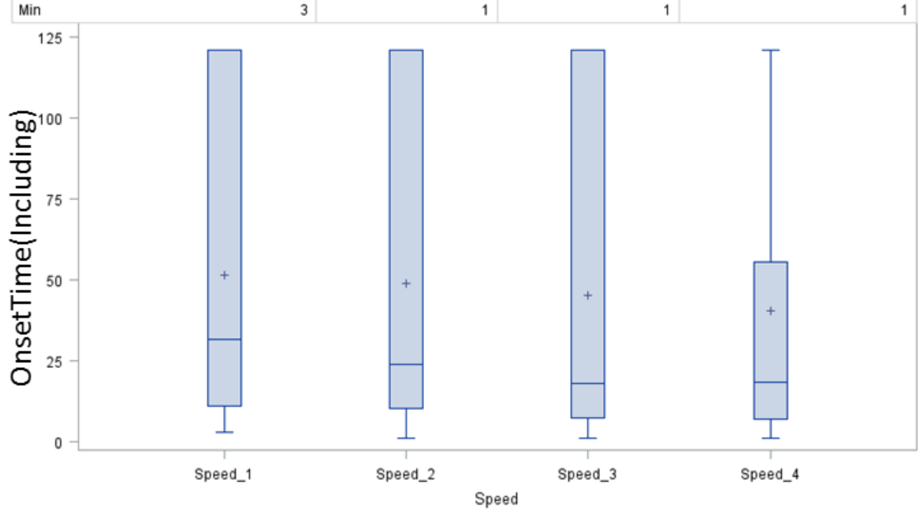

Figure 3.7.a: Main Effects of Stimuli Speed in Experiment 1 on Onset time including no-vection cases

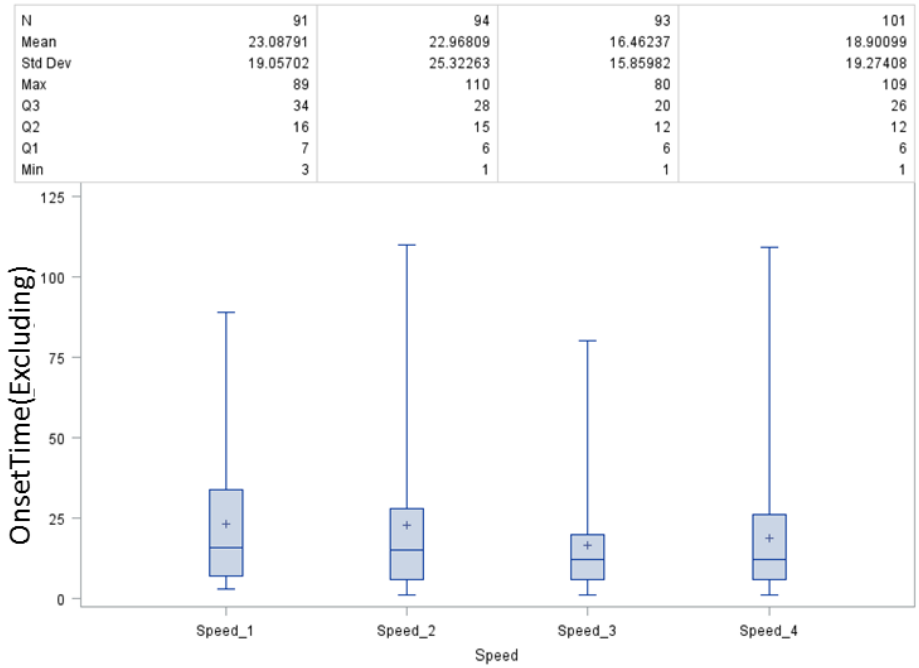

Figure 3.7.b: Main Effects of Stimuli Speed in Experiment 1 on Onset time excluding no-vection cases

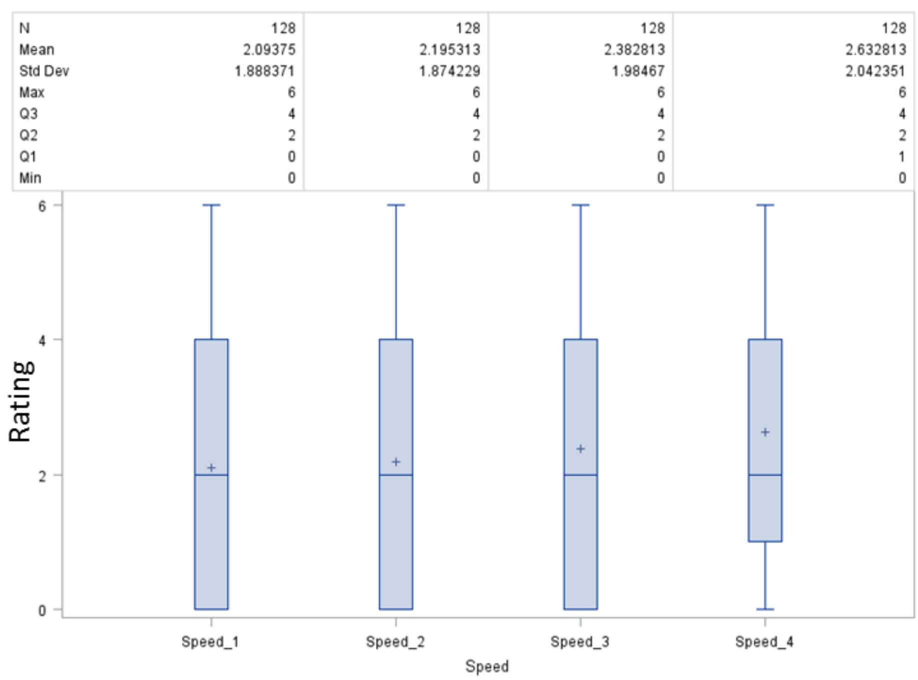

Figure 3.7.c: Main Effects of Stimuli Speed in Experiment 1 on Rating

	OnsetTime_Including	OnsetTime_Excluding	Rating
Speed_1	A	A	A
Speed_2	A	AB	AB
Speed_3	B	B	B
Speed_4	B	B	C

Table 3.2: Post-hoc analysis on speed. Speed levels that are significantly different from each other do not share any common letters ($p<0.05$).

3.2.2.5. Interaction Effects of Ceiling Light and Frontal Occultation

When the ceiling light is on, holding the cardboard causes significantly shorter OnsetTime_Including than staring at the LED ($p<0.0001$). However, when the ceiling light is off, there is no significant difference between the onset times of hold the cardboard and staring at the LED ($p>0.1$).

Based on the OnsetTime_Including findings, one may argue that blocking the frontal vision does not cause any significant difference when the ceiling light is off because subject cannot see the visual cues available in the room even when he/she doesn't hold the cardboard.

However, this interaction effect does not occur for OnsetTime_Excluding and Rating.

3.2.2.6. Interaction Effects of Ceiling Light and Stimuli Speed

When the ceiling light is off, speed significantly affects all of the vection measures, i.e. OnsetTime_Including ($p<0.0001$; Friedman Test), OnsetTime_Excluding ($p<0.05$; Kruskal-Wallis Test), Rating ($p<0.0001$; Friedman Test). However, when the ceiling light is on, speed doesn't affect any of the vection measures significantly ($p>0.1$).

3.2.2.7. Interaction Effects of Stimuli Direction and Frontal Occultation

Downward direction of stimuli causes higher vection ratings when the subject holds the cardboard ($p<0.05$). However, when the subject stares at the LED, there is no significant difference between the vection ratings of downward and upward directions of the stimuli ($p>0.1$).

This interaction effect does not occur for OnsetTime_Including and OnsetTime_Excluding. Moreover, as mentioned above, stimuli direction doesn’t appear in the main effect.

3.3. Experiment 2 (the Dark-adaptation-Exp.)

3.3.1. Methods of Experiment 2 (the Dark-adaptation –Exp.)

3.3.1.1. Subjects

13 self-reported healthy subjects (10 male) were recruited into the second experiment. Majority of the subjects of the second experiment had taken the first experiment too. In order to minimize the learning effect and design the best follow up experiment of the previous one, Experiment 2 was conducted approximately 8 months after Experiment 1.

The age of the subjects of the second experiment ranged from 18 to 31 years with a mean of 24 and median of 24 years. All of the subjects had normal or corrected to normal vision according to 20/20 protocol. After the experiment procedure was introduced, all subjects gave a written consent knowing that they can withdraw anytime from the experiment upon their request.

3.3.1.2. Setup of Experiment 2 (Dark-adaptation Exp.)

The same equipment and stimuli as Experiment 1 were used.

3.3.1.2. Design and Procedure of Experiment 2 (Dark-adaptation Exp.)

The experimental design of the Experiment 2 is similar to Experiment 1 with two main differences. First, ceiling light on and ceiling light off conditions were conducted in separate sessions in Experiment 2. The second difference between the Experiment 2 and Experiment 1 is that Experiment 2 had only the highest and lowest levels of the speed in Experiment 1 (i.e. Speed_1 and Speed_4).

In the beginning of ceiling light off session, the ceiling light was turned off and the subject stayed in the room for 20 minutes to let his/her eyes adapt to dark condition before the experimental testing in that session started. Even when the ceiling light was off, the room was not in complete darkness because of the little light coming out of the stimuli monitors and the small LED that was used for fixating the eyes.

Similarly, for the lights on session, subjects waited in normal lighting for 20 minutes before experimental testing in that session started. The order of the two sessions was randomized across subjects.

3.3.2. Results of Experiment 2 (Dark-adaptation Exp.)

Similar to Experiment 1, the independent variables of Experiment 2 were (i) Ceiling light (ON/OFF), (ii) Frontal occultation (Holding a cardboard / Staring at an LED), (iii) Direction of stimuli (Downward/Upward), (iv) Speed (2 levels). The dependent variables were OnsetTime_Including, OnsetTimeExcluding, and Rating.

Main effects of Experiment 2 are similar to those of Experiment 1. In other words, most of the major findings above are true even after eye adaptation.

3.3.2.1. Main Effects of Ceiling Light in Experiment 2 (i.e. After dark/light adaptation)

Compared to keeping the ceiling light ON, keeping the ceiling light OFF causes significantly shorter OnsetTime_Including (p<0.0001; Wilcoxon Signed-Rank Test), shorter OnsetTime_Excluding (p<0.0001; Mann-Whitney U Test), and significantly higher vection ratings (p<0.0001; Wilcoxon Signed-Rank Test). Therefore, keeping the ceiling light off causes significantly more compelling vection even after eyes are adapted to dark/light.

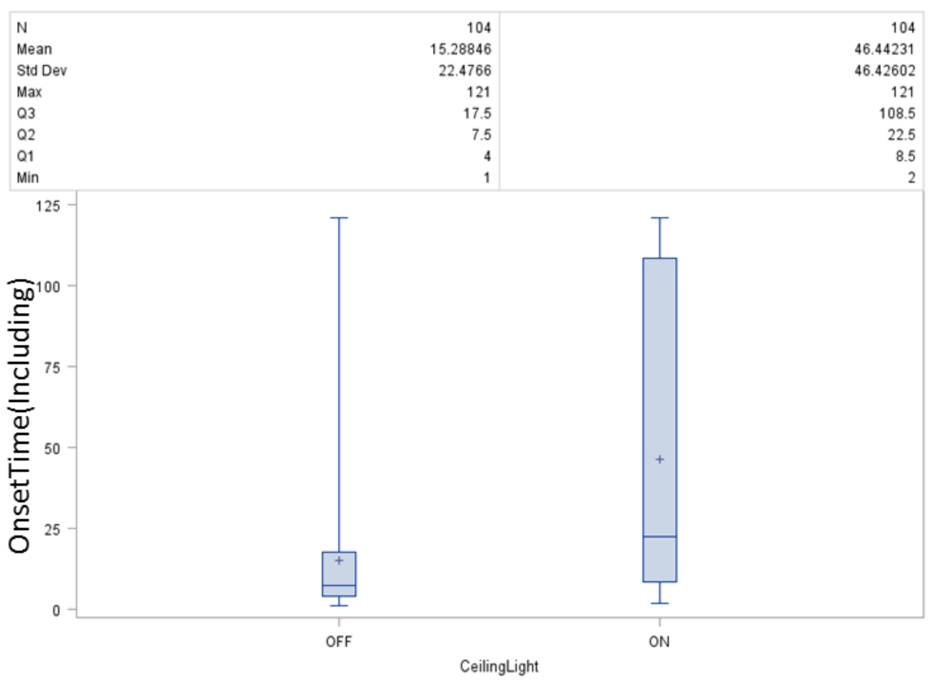

Figure 3.8.a: Main Effects of Ceiling Light in Experiment 2 on Onset time including no-vection cases

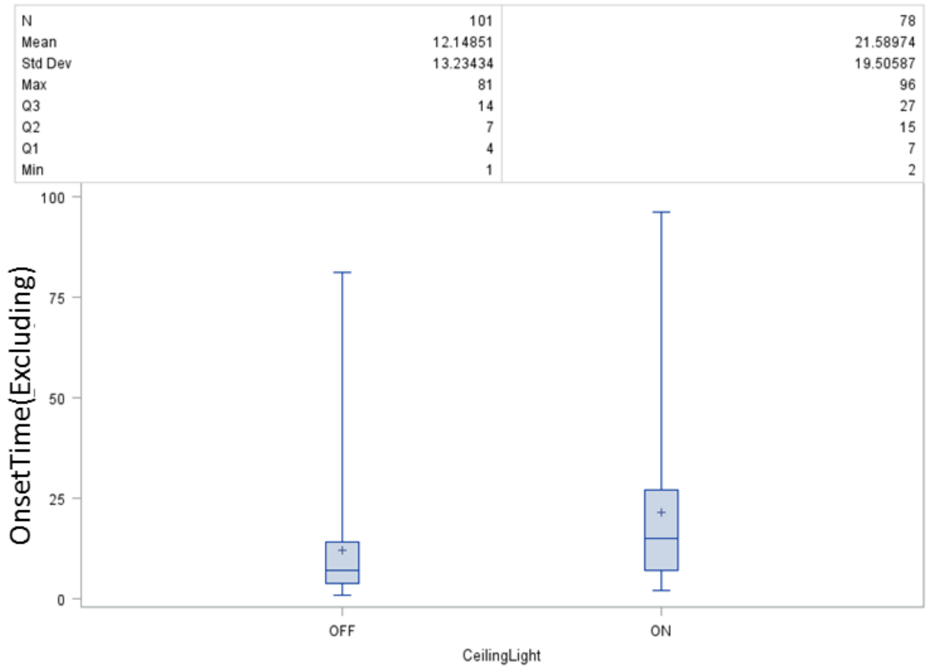

Figure 3.8.b: Main Effects of Ceiling Light in Experiment 2 on Onset time excluding no-vection cases

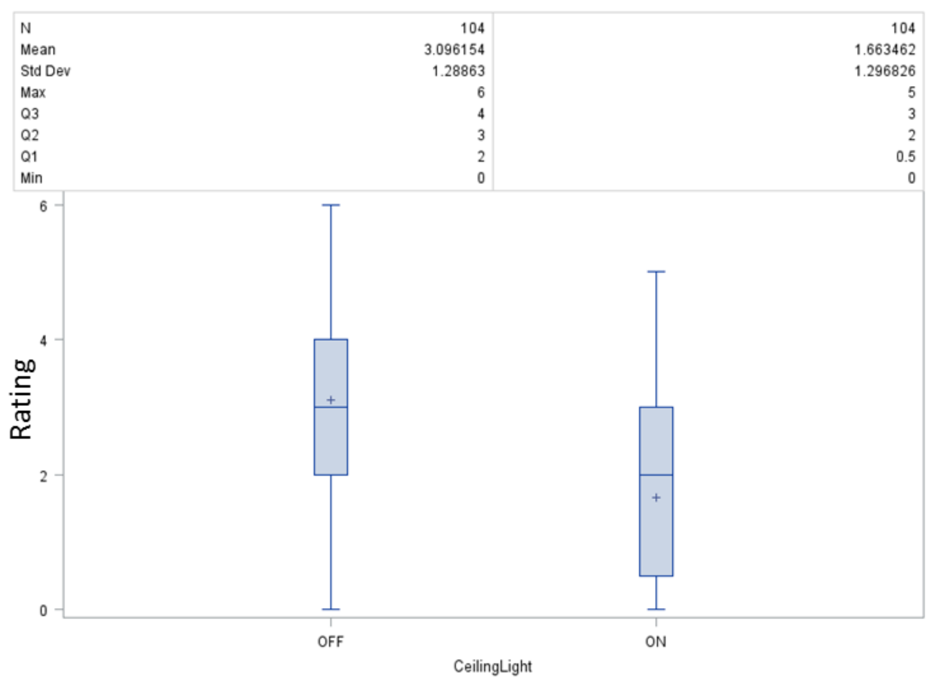

Figure 3.8.c: Main Effects of Ceiling Light in Experiment 2 on Rating

3.3.2.2. Main Effects of Frontal Occultation in Experiment 2 (i.e. After dark/light adaptation)

Compared to staring at an LED with open view, holding a cardboard to block central vision causes significantly shorter OnsetTime_Including ($p<0.0001$; Wilcoxon Signed-Rank Test), shorter OnsetTime_Excluding ($p<0.05$; Mann-Whitney U Test), and significantly higher vection ratings ($p<0.0001$; Wilcoxon Signed-Rank Test).

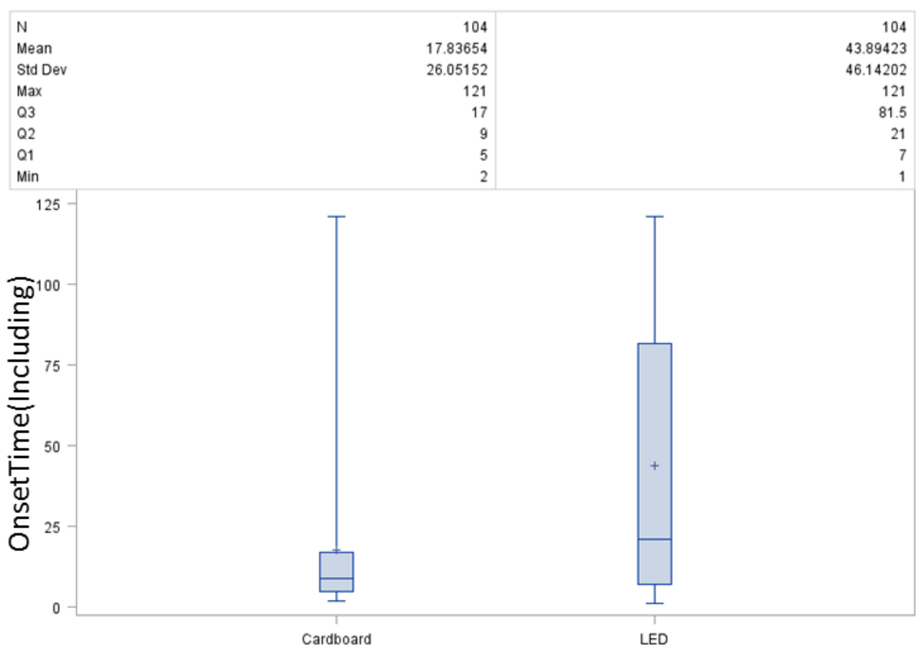

Figure 3.9.a: Main Effects of Frontal Occultation in Experiment 2 on Onset time including no-vection cases

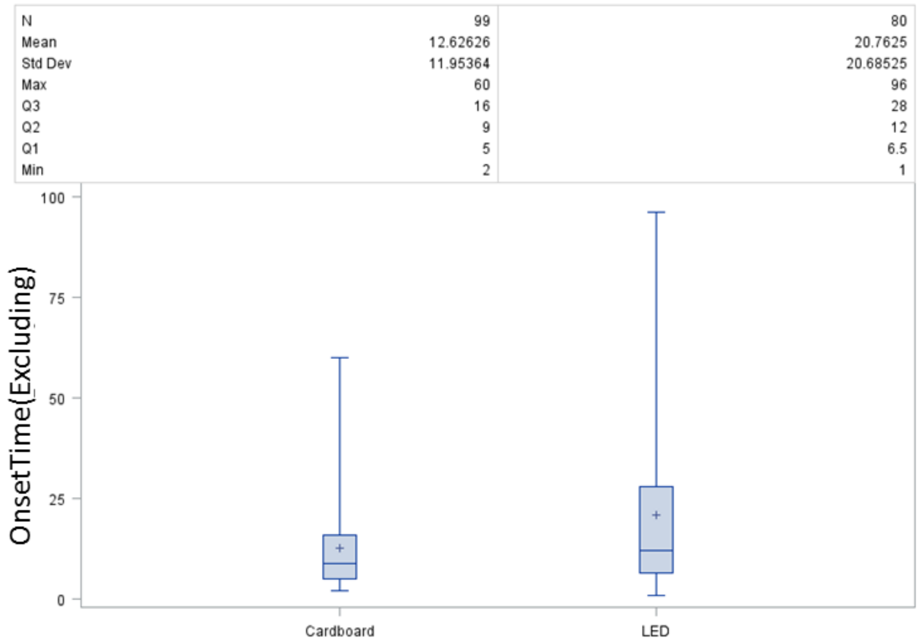

Figure 3.9.b: Main Effects of Frontal Occultation in Experiment 2 on Onset time excluding no-vection cases

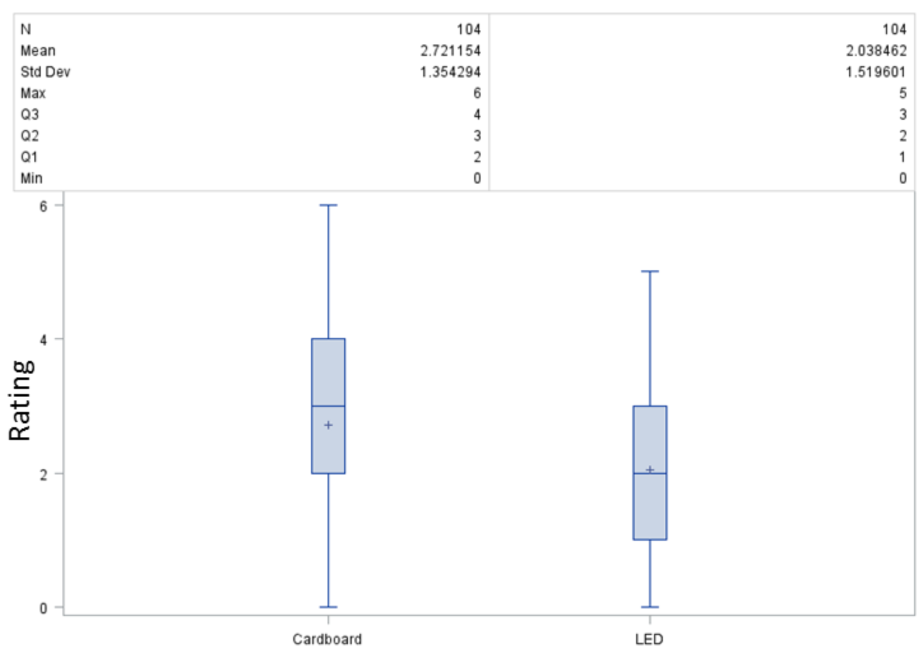

Figure 3.9.c: Main Effects of Frontal Occultation in Experiment 2 on Rating

3.3.2.3. Main Effects of Stimuli Direction in Experiment 2 (i.e. After dark/light adaptation)

Stimuli direction does not have any significant main effect on any of the vection measures i.e. OnsetTime_Including (p>0.1; Wilcoxon Signed-Rank Test), OnsetTime_Excluding (p>0.1; Mann-Whitney U Test), Rating (p>0.1; Wilcoxon Signed-Rank Test). Therefore, upward and downward stimuli have same effect on vection onset times and rating.

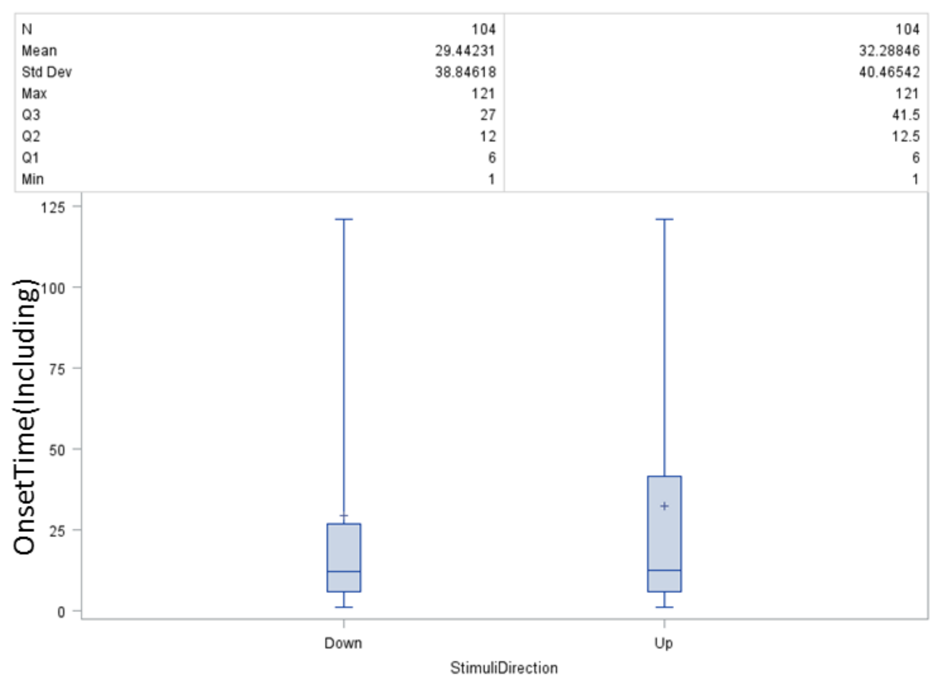

Figure 3.10.a: Main Effects of Stimuli Direction in Experiment 2 on Onset time including no-vection cases

	Down	Up
N	90	89
Mean	15.2	17.33708
Std Dev	14.92092	18.68272
Max	81	96
Q3	19	21
Q2	11	10
Q1	6	5
Min	1	1

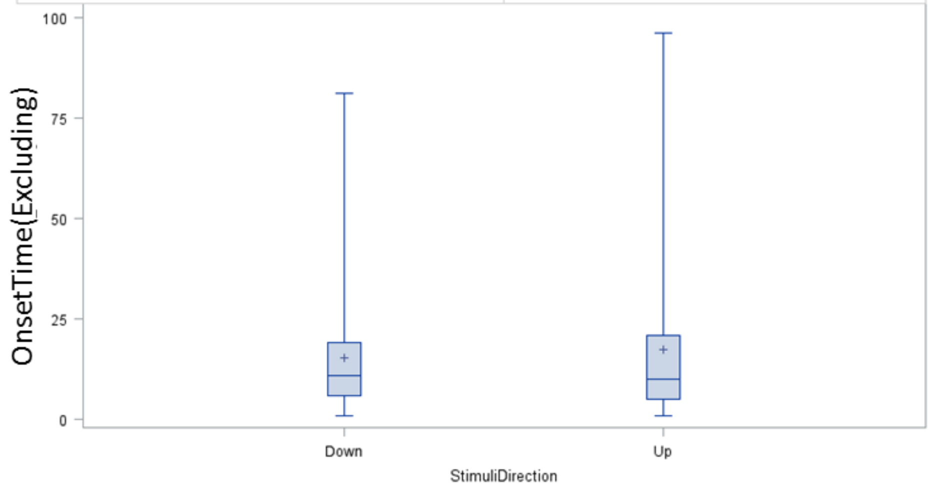

Figure 3.10.b: Main Effects of Stimuli Direction in Experiment 2 on Onset time excluding no-vection cases

	Down	Up
N	104	104
Mean	2.346154	2.413462
Std Dev	1.446584	1.511192
Max	5	6
Q3	3	4
Q2	3	2
Q1	1	1
Min	0	0

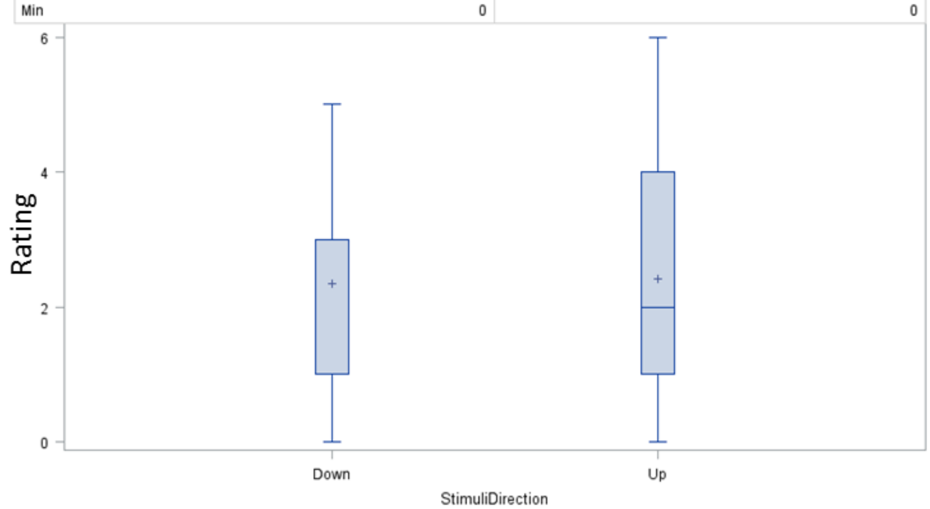

Figure 3.10.c: Main Effects of Stimuli Direction in Experiment 2 on Rating

3.3.2.4. Main Effects of Stimuli Speed in Experiment 2 (i.e. After dark/light adaptation)

Compared to lower speed (i.e. Speed_1), higher speed (i.e. Speed_4) causes significantly shorter OnsetTime_Including ($p<0.0001$; Wilcoxon Signed-Rank Test), and significantly higher vection ratings ($p<0.0001$; Wilcoxon Signed-Rank Test). However, the difference between Speed_1 and Speed_4 is not significant measured in terms of OnsetTime_Excluding ($p>0.05$; Mann-Whitney U Test).

	Speed_1	Speed_4
N	104	104
Mean	36.56731	25.16346
Std Dev	42.85509	35.33202
Max	121	121
Q3	46	22.5
Q2	14.5	10
Q1	7	5
Min	2	1

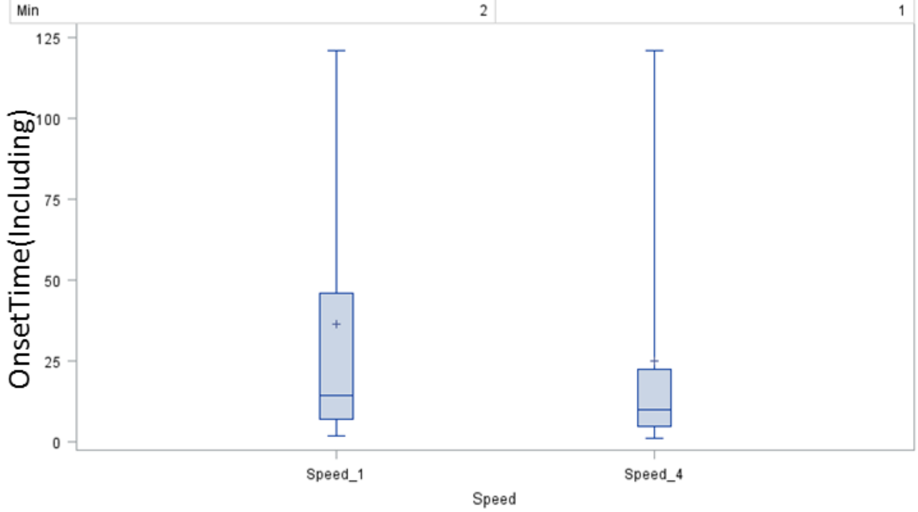

Figure 3.11.a: Main Effects of Stimuli Speed in Experiment 2 on Onset time including no-vection cases

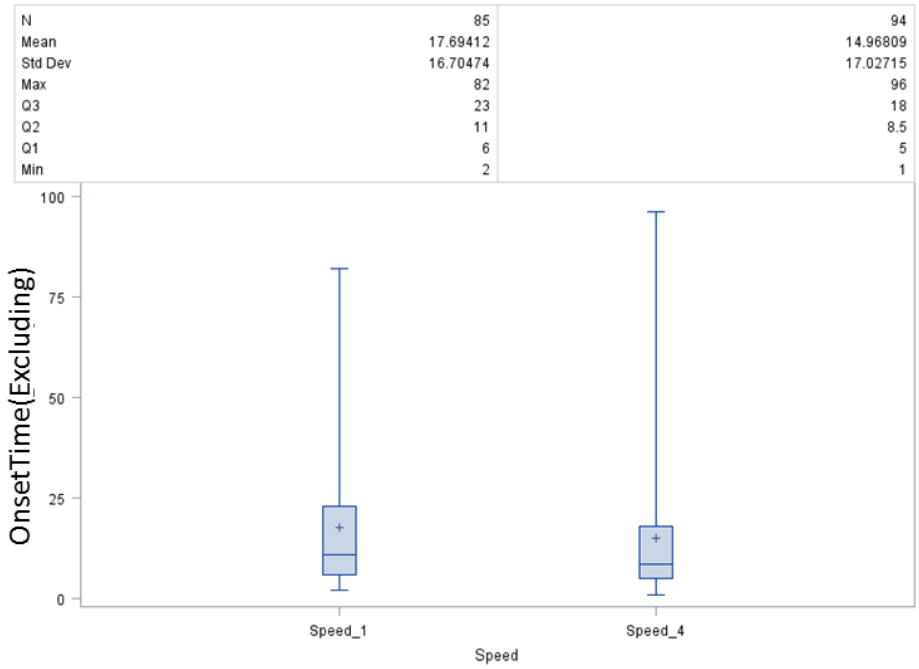

Figure 3.11.b: Main Effects of Stimuli Speed in Experiment 2 on Onset time excluding no-vection cases

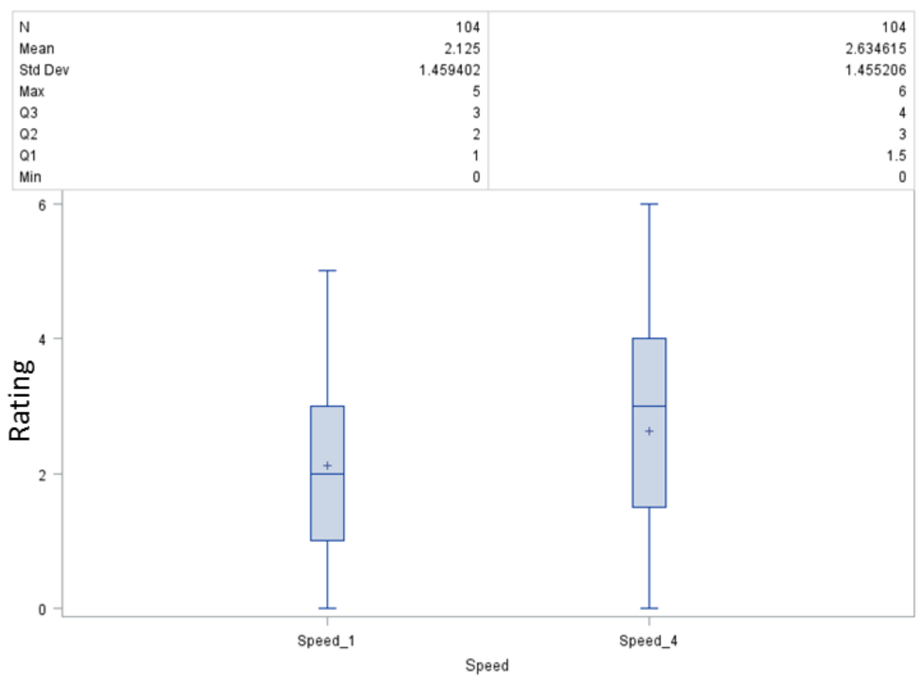

Figure 3.11.c: Main Effects of Stimuli Speed in Experiment 2 on Rating

3.3.2.5. Interaction Effects of Ceiling Light and Frontal Occultation in Experiment 2 (i.e. After dark/light adaptation)

When the ceiling light was on, holding the cardboard causes significantly shorter OnsetTime_Excluding than staring at the LED ($p<0.0001$). However, when the ceiling light was off, there is no significant difference between the onset times of hold the cardboard and staring at the LED ($p>0.1$).

Based on the OnsetTime_Excluding findings, one may argue that blocking the frontal vision does not cause any significant difference when the ceiling light was off because subject cannot see the visual cues available in the room even when he/she doesn't hold the cardboard. (It is interesting to note that the same argument was reached based on the OnsetTime_Including results of Experiment 1.)

However, this interaction effect does not occur for OnsetTime_Including and Rating.

3.3.2.6. Interaction Effects of Ceiling Light and Stimuli Speed in Experiment 2 (i.e. After dark/light adaptation)

When the ceiling light is off, higher speed (i.e. Speed_4) causes significantly shorter OnsetTime_Excluding ($p<0.05$; Mann-Whitney U Test), and significantly higher Rating ($p<0.001$; Wilcoxon Signed-Rank Test). But, when the ceiling light is on, speed doesn't affect OnsetTime_Excluding or Rating ($p>0.1$).

However, this interaction effect does not occur for OnsetTime_Including.

3.3.2.7. Interaction Effects of Stimuli Direction and Frontal Occultation in Experiment 2 (i.e. After dark/light adaptation)

This interaction effect has not showed up in Experiment 2 although it has appeared in Experiment 1.

3.4. Discussion of Results of Experiment 1 (Preliminary Exp.) and Experiment 2 (Dark-adaptation Exp.)

3.4.1. Revisit of Hypotheses of This Thesis in the Lights of Results of Experiment 1 and Experiment 2

3.4.1.1. H1: If we eliminate bias from Johansson's study, 1x47 FOV doesn't cause vection

Johansson (1977) presented stimuli of 10x47 degree bands first and reduced it to 9x47 degree if a subject reported vection. A subject may have bias to report vection to 9x47 degree FOV if he/she has already reported vection to just a little wider size of the same stimuli. But Johansson followed this procedure by reducing the horizontal FOV at steps of 1 degree, until the minimum horizontal FOV was reached, for the subjects who reported vection. In order to eliminate this bias, our Experiment 1 and 2 have only included 1x47 degree FOV stimuli; and it was possible for all of the subjects to experience vection at such a narrow FOV under certain conditions. Therefore, results of Experiment 1 and 2 do not support H1.

It has to be acknowledged that subjects of Experiment 1 have taken part in training with 10x47 degree FOV before the experiment starts. But this procedure is not supposed to cause Johansson's bias because 10x47 degree FOV was shown during the pre-experimental training only.

Moreover, the training sessions were only done for Experiment 1. Experiment 2 and other experiments that will be discussed in the future chapters of this thesis didn't have training with 10x47 degree FOV. For example, in Experiment 3, 11 new subjects who have never been trained with 10x47 degree FOV, experienced vection for 1x40 degree FOV directly. Therefore, even after removing the bias, such a narrow FOV can cause compelling vection.

Our study shows that providing a large field of view is not a necessary element of causing compelling vection. A narrow strip of falling/rising dots can even cause very compelling vection at FOV of 1° horizontal x 47° vertical.

3.4.1.2. H2.A: Ceiling Light off causes more compelling vection & H2.B: Ceiling Light off and on are similar after eye adaptation

Experiment 1 showed that keeping ceiling light off causes shorter vection onset times (both including and excluding no-vection cases), and higher vection ratings. This supports H2.A.

As H2.B states, we expected the difference between “on and off” to disappear after eyes are adapted to darkness. However, results of Experiment 2 showed that ceiling light off is still more compelling even after eye adaptation. Therefore, H2.B is not supported by Experiment 2.

There is a great number of vection studies conducted in dark environment in the literature; and there is a big number of vection studies conducted in normal lighting as well. The findings of these studies may enlighten the research of motion sickness and vection a lot. However, here, we want to indicate that the claims of a study under a dark environment cannot be generalized to that of a normal lighting environment, and vice versa.

3.4.1.3. H3: Blocking the central vision causes more compelling vection

Subjects of Johansson (1977) used their own hands to block their central vision; and found out that it is more compelling than open view. In our Experiment 1 and 2, we blocked the central vision with a cardboard; and found that holding a cardboard is more compelling than staring at an LED with open view. Therefore, findings of Experiment 1 and 2 support H3.

Holding a cardboard reduces the amount of earth-fixed cues coming to the subject’s eyes. Moreover, it facilitates the stimuli to be perceived as background. For the without cardboard condition, it is more difficult for subject to differentiate the stimuli to be background as there are many visual cues in the same environment as him/her which were perceived as foreground.

3.4.1.4. H4: Stimuli direction does not affect vection strength

Main effects of both Experiment 1 and 2 support H4 showing that stimuli direction does not affect vection measures.

However, in Experiment 1, there was an interaction effect of Stimuli Direction and Frontal Occultation. When subjects hold the cardboard, downward stimuli causes higher vection ratings. But this interaction hasn't appeared for any other vection measures (i.e. OnsetTime_Including and OnsetTime_Excluding).

Moreover, in Experiment 2, neither main effect nor interaction effect of stimuli direction was significant. Therefore, H4 is supported by Experiment 2.

3.4.1.5. H5: Stimuli speed affects vection strength

Based on results of Experiment 1 and 2, we can claim that the higher speed (within the range we have tested), the more compelling the vection (although not every pair is significantly different). This effect shows up in the main effect analysis.

When the lights are on, the speed seems not to affect vection measures (except for OnseTime_Including of Experiment 2). However, when the lights are off, speed affects vection. Therefore, H5 is supported when the lights are off; but mainly not supported when the lights are on.

It is interesting to note that Johansson conducted his experiments in normal lighting condition; and claimed that speed does not affect vection within certain limits. This is parallel to our findings.

3.4.2. Comparison of Our Findings with Johansson (1977)

Johansson (1977) used a similar stimuli under normal lighting condition and found that 6.67% of his subjects reported vection when their frontal vision was clear of any obstacle; and 80% of them reported vection when their frontal vision was blocked with their own hands. In our Experiment 1 and 2, the percentage of subjects who reported vection reached 100% when the ceiling light was off, the speed level was set to Speed_4, and the subjects hold the cardboard. In other words, our study provides the conditions for inducing vection more.

Johansson (1977) used black dots on a white background. However, we used white dots on a black background because we believe that this stimulus is more suitable to darkness as the remaining of the dark room may be perceived as the continuation of the background of the stimulus screens.

3.4.3. Further Discussion on Measures of Vection

Johansson (1977) used vection onset time as the only criterion to measure vection. Other researchers employed other methods like subjective rating of relative speed (Allison et al., 1999), convincingness level of vection (Trutoiu et al., 2009), and simulator sickness ratings (Trutoiu et al., 2009).

Intuitively, it may be assumed that all of the vection measures mentioned in the previous paragraph are correlated to each other; and measuring only one of them may be enough to make thorough conclusions. However, it is not always the case. For example, in this thesis, we employed vection onset time and subjective rating of relative speed; and we found that the responses of the onset time and subjective rating are not always same to the factors that we analyzed in this study.

3.4.4. Framing Vection

In our experiments, stimuli areas were framed with black color plates which naturally reflected a portion of light emitted by the stimuli displays. Bos et al. (2015) demonstrated that earth-fixed cues like frame of the stimulus display reduce the effect of stimulus on postural sway, subjective visual vertically, and motion sickness. Based on these facts, we can assume that vection is less compelling when there are framing cues. Therefore, in order to get rid of vection frame to intensify vection, goggles with appropriate transmittance levels can be used so that only the stimuli area will be visible but not the frame. In this way, vection can become more compelling which will increase visually induced motion sickness symptoms as well. Based on the above discussion, if our experiments had been conducted with such reflective goggles, we would have encountered higher vection ratings.

CHAPTER 4: EXPERIMENT 3: VECTION PERCEPTION WITH NARROW (1 DEGREE) AND SHORT (5 DEGREES) VISUAL MOTION

4.1. Introduction to Experiment 3

Results of Experiments 1 and 2 demonstrate that two stimuli, constituted of random dot pattern, covering 1 degree horizontal by 47 degrees vertical FOV can cause compelling vection when they are placed at 70 degree horizontal location on each side of the subject. The FOV of 1x47 degrees was used in order to follow the study by Johansson (1977). There is no study with narrow stimuli of shorter than 47 degrees vertical FOV. If we reduce the vertical FOV, the stimulating factor to the subject will be less; but we may still be able to induce vection. In Experiment 3, we investigated the effect of vertical FOV on vection. In particular, we hypothesize that a visual motion with a narrow FOV (1 degree horizontal) and short FOV (5 degrees vertical) (one stripe on each side) can cause vection (Hypothesis 6). Experiment 3 was also referred as the Short-FOV Exp.

When a subject observes two stripes of falling (/rising) dots, he/she perceives an upward (/downward) self-motion as if inside a lift/elevator (when ceiling light is on), or in space observing a star-field (when ceiling light is off). However, when dots on one side go down and the dots on other side go up, the stimuli represent a circular rotation although stimuli itself is not in a curved-shape. Trutoiu et al. (2009) claimed that circular vection may be more compelling than linear vection based on their experiments. In order to test their claim and find a more compelling vection stimulus, we compared circular and linear vection in Experiment 3. (Hypothesis 7)

4.2. Methods of Experiment 3 (Short-FOV Exp.)

4.2.1. Subjects of Experiment 3 (Short-FOV Exp.)

16 self-reported healthy subjects (11 male) were recruited into the Experiment 3. The age of the subjects ranged from 18 to 31 years with a mean of 23.6 and median of 23 years. All of the subjects were tested to have normal or corrected to normal vision according to 20/20 protocol. After the experiment procedure was introduced, all subjects gave a written consent knowing that they can withdraw anytime from the experiment upon their request.

4.2.2. Setup and Procedure of Experiment 3 (Short-FOV Exp.)

The same setup and procedure as Experiment 1 and 2 were used in Experiment 3 with below exceptions.

The speed of the dots was set to 20 cm/s (approximately 24deg/s). And the computer program was modified to present the desired vertical FOV levels and directions (i.e. up/down for each monitor) that are tested in Experiment 3.

Ceiling light was kept off and the cardboard is fixed in front of the subjects because these conditions were found more compelling in Experiment 1 and 2. Also each session of Experiment 3 started with an eye adaptation period of 20 minutes resting after the ceiling light was turned off.

4.2.3. Design of Experiment 3 (Short-FOV Exp.)

Independent variables of Experiment 3 are vertical FOV (5, 10, 20, 40 degrees), and stimuli direction (upward, downward, clockwise, anti-clockwise). It has to be noted that vection type (i.e. circular type and linear type) is an intrinsic factor of stimuli direction as clockwise and anti-clockwise are circular; whereas upward and downward are linear.

The factors that are fixed at a level and not changed during the experiment are horizontal location (at 70 degree), horizontal FOV (1 degree width), Ceiling Light (off), Frontal Occultation (fixing cardboard in front of the subject), stimuli speed (20cm/s which is approximately 24deg/s).

Vection was measured in the same way as previous two experiments (i.e. OnsetTime_Including, OnsetTime_Excluding, and Rating).

4.3. Results of Experiment 3 (Short-FOV Exp.)

4.3.1. Main Effects of Vection Type

Compared to circular stimuli, linear stimuli causes significantly shorter OnsetTime_Including ($p<0.0001$; Wilcoxon Signed-Rank Test), shorter OnsetTime_Excluding ($p<0.001$; Mann-Whitney U Test), and significantly higher vection ratings ($p<0.0001$; Wilcoxon Signed-Rank Test). In other words, linear stimuli cause more compelling vection than circular stimuli. (See Figure 4.1)

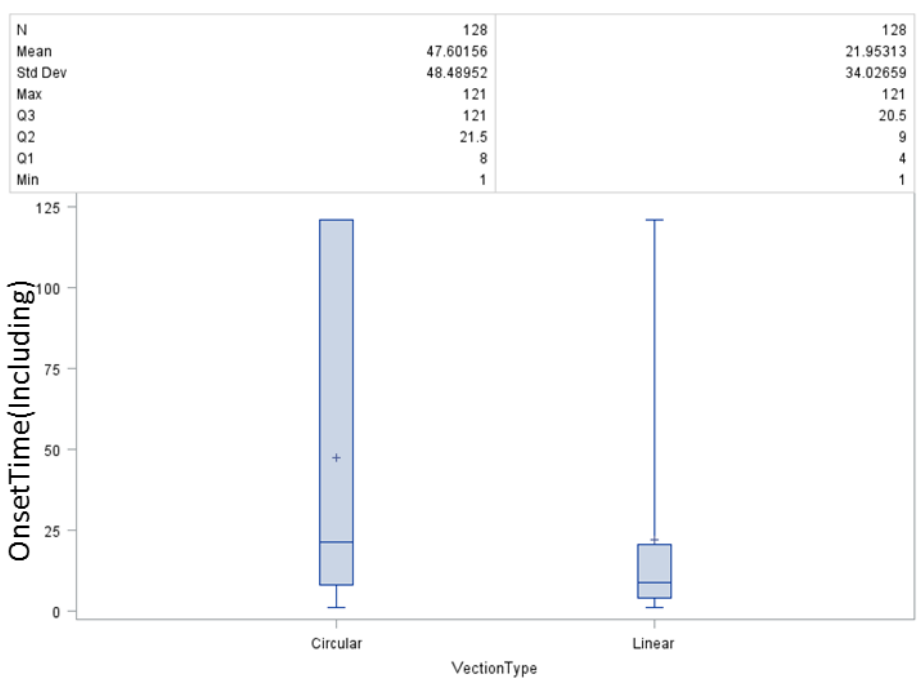

Figure 4.1.a: Main Effects of Vection Type on Onset time including no-vection cases

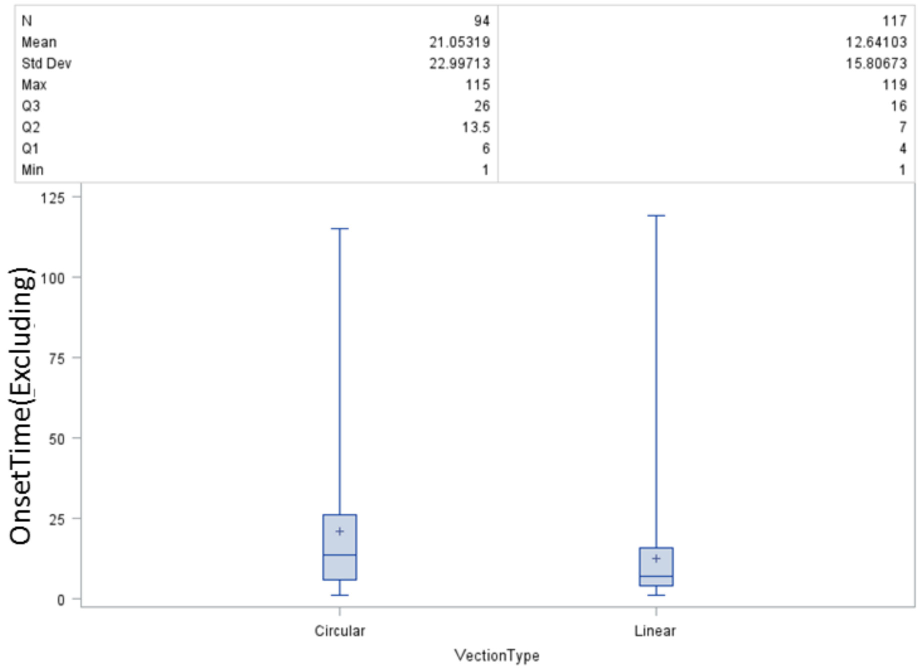

Figure 4.1.b: Main Effects of Vection Type on Onset time excluding no-vection cases

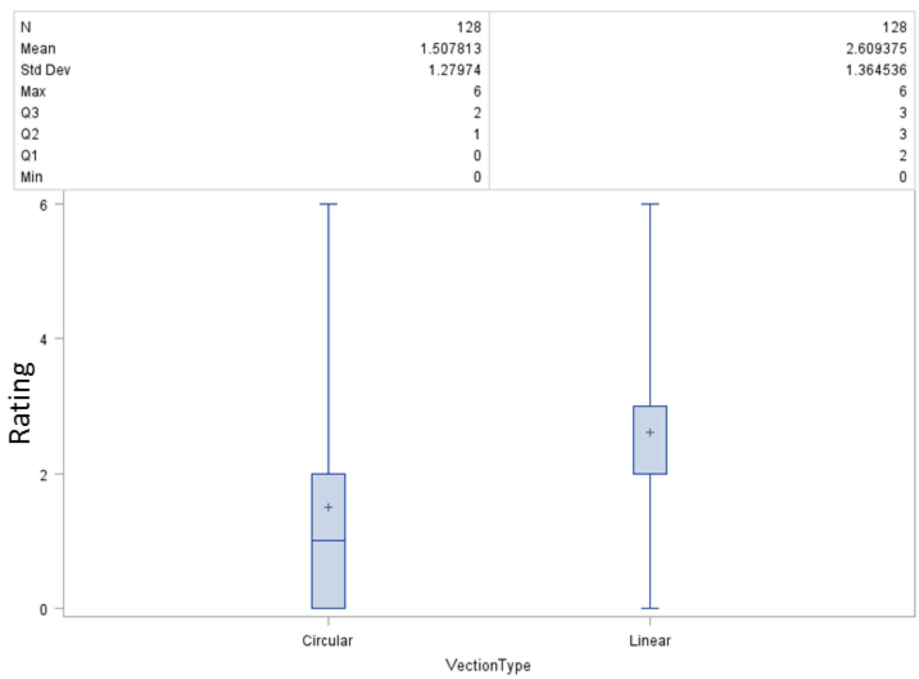

Figure 4.1.c: Main Effects of Vection Type on Rating

4.3.2. Main Effects of Stimuli Direction

Although linear type is more compelling than circular type stimuli, there is no significant difference between neither upward versus downward; nor clockwise versus anti-clockwise for any of the vection measures, i.e. OnsetTime_Including (Wilcoxon Signed-Rank Test), OnsetTime_Excluding (Mann-Whitney U Test), Rating (Wilcoxon Signed-Rank Test) ($p>0.05$). (See Figure 4.2)

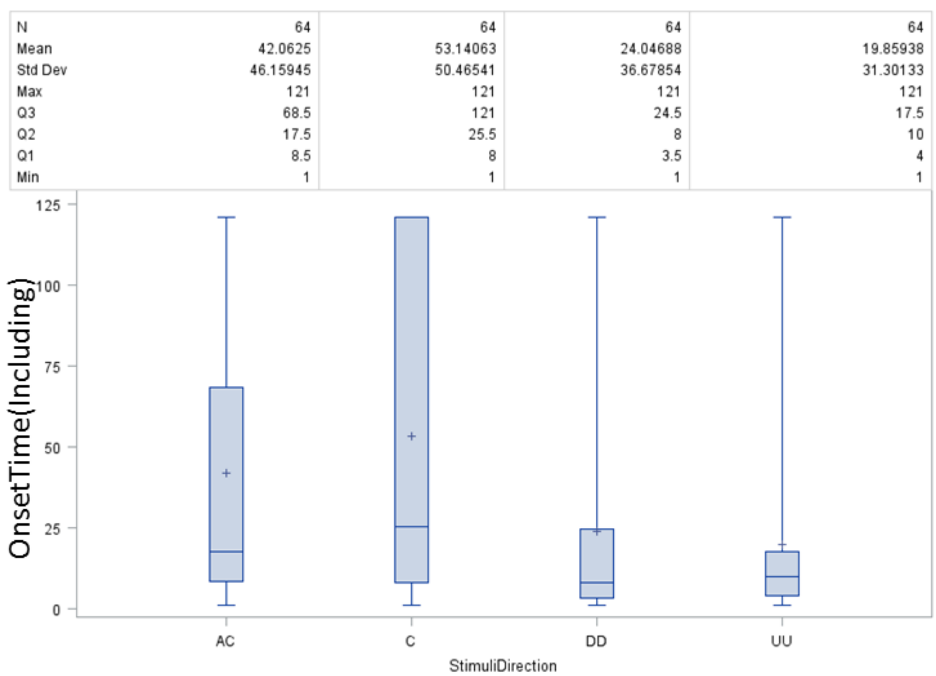

Figure 4.2.a: Main Effects of Stimuli Direction on Onset time including no-vection cases

	AC	C	DD	UU
N	50	44	57	60
Mean	19.96	22.29545	12.14035	13.11667
Std Dev	21.46279	24.81802	13.93536	17.50554
Max	115	110	67	119
Q3	23	26.5	15	16
Q2	12.5	14.5	7	9
Q1	7	6	3	4
Min	1	1	1	1

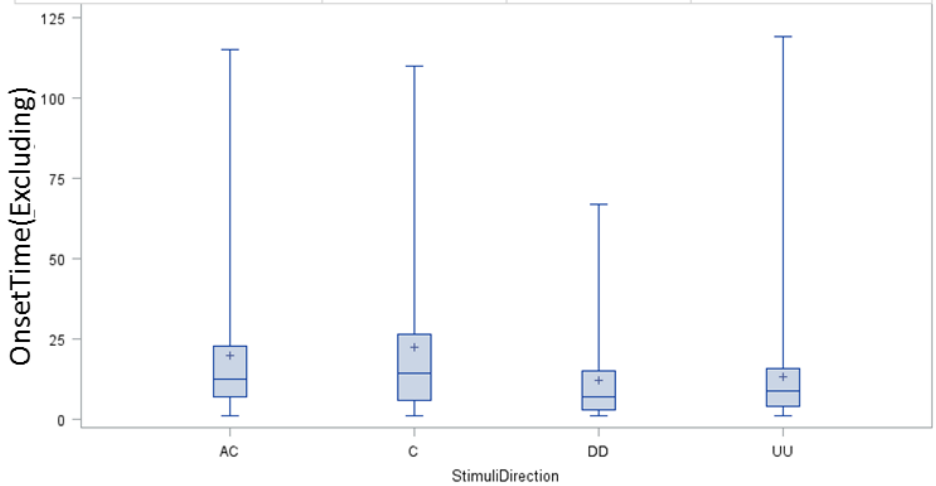

Figure 4.2.b: Main Effects of Stimuli Direction on Onset time excluding no-vection cases

	AC	C	DD	UU
N	64	64	64	64
Mean	1.578125	1.4375	2.546875	2.671875
Std Dev	1.306937	1.258306	1.435709	1.297797
Max	6	4	6	5
Q3	2	2.5	3	4
Q2	1	1	3	3
Q1	1	0	2	2
Min	0	0	0	0

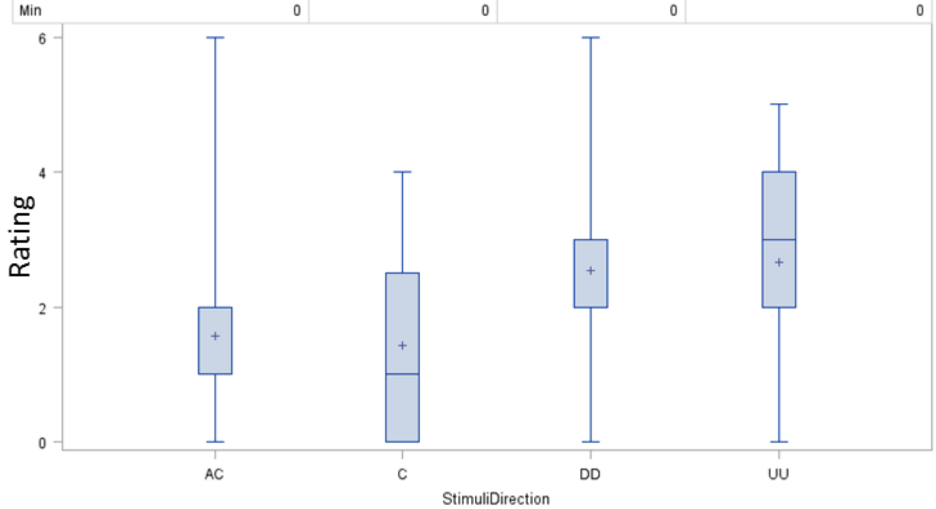

Figure 4.2.c: Main Effects of Stimuli Direction on Rating

4.3.3. Main Effects of Vertical FOV

Vertical FOV affects OnsetTime_Including ($p<0.0001$; Friedman Test), and Rating ($p<0.01$; Friedman Test). Although Kruskal-Wallis Test was unable to detect a significant effect of FOV on OnsetTime_Excluding ($p>0.05$), Mann-Whitney U Test on each pair showed that 5 degree causes significantly shorter OnsetTime_Excluding. (See Figure 4.3)

For each of the vection measure, the general trend seems like the shorter the vertical FOV, the less compelling the vection although not every pair strictly follows it. A post-hoc analysis with Wilcoxon Signed-Rank Test (for OnsetTime_Including and Rating) and Mann-Whitney U Test (for OnsetTime_Excluding) on each pair showed the pairs that are significantly different. (See Table 4.1)

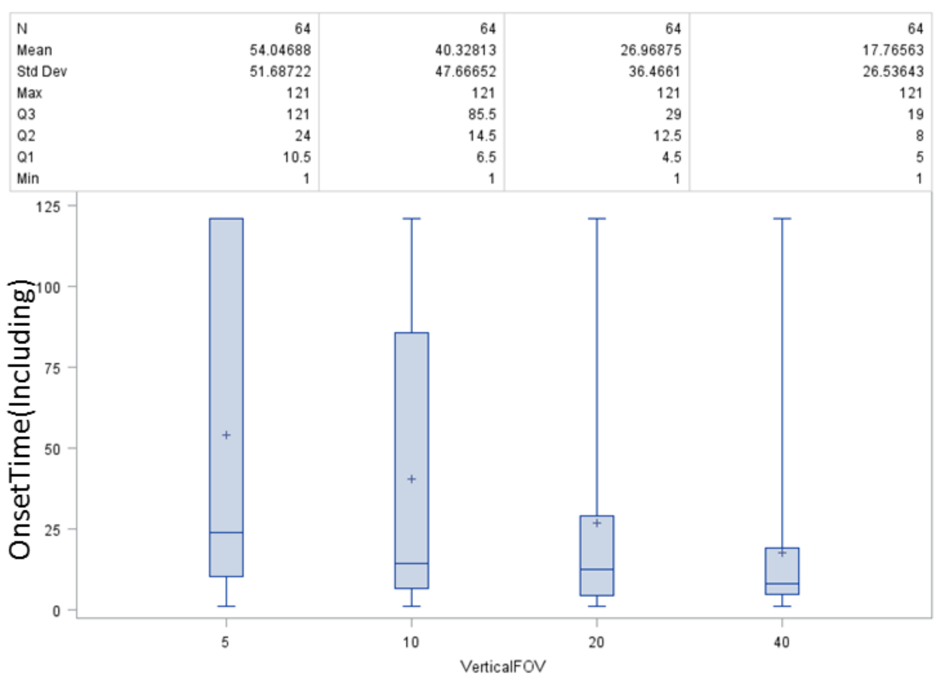

Figure 4.3.a: Main Effects of Vertical FOV on Onset time including no-vection cases

N	42	49	58	62
Mean	18.97619	15.63265	17.24138	14.43548
Std Dev	20.97093	18.0505	21.04157	19.14622
Max	119	92	115	110
Q3	23	24	19	18
Q2	13.5	10	10.5	8
Q1	5	5	4	5
Min	1	1	1	1

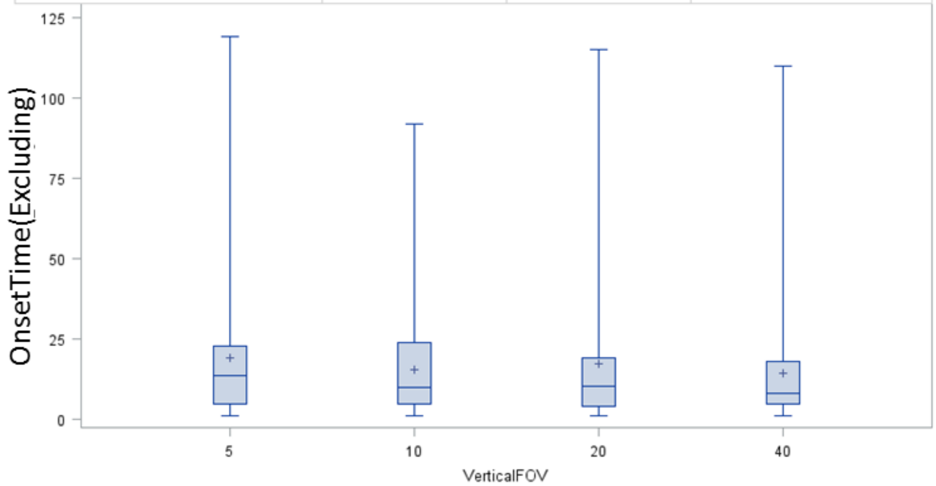

Figure 4.3.b: Main Effects of Vertical FOV on Onset time excluding no-vection cases

N	64	64	64	64
Mean	1.390625	1.671875	2.3125	2.859375
Std Dev	1.364135	1.297797	1.295597	1.319779
Max	6	5	6	6
Q3	2	3	3	3.5
Q2	1	2	2	3
Q1	0	1	1.5	2
Min	0	0	0	0

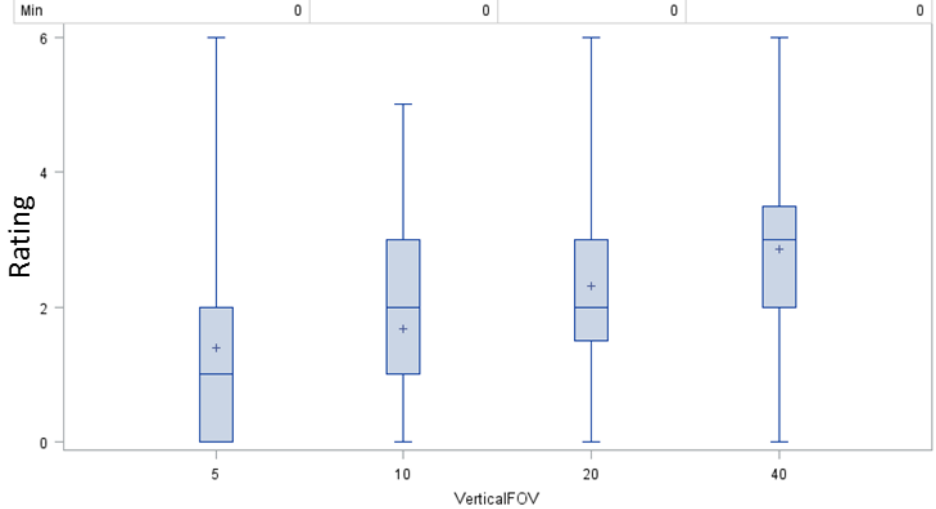

Figure 4.3.c: Main Effects of Vertical FOV on Rating

	OnsetTime_Including	OnsetTime_Excluding	Rating
5 degree	A	A	A
10 degree	B	AB	A
20 degree	C	AB	B
40 degree	D	B	C

Table 4.1: Post-hoc analysis on vertical FOV. Levels that are significantly different from each other do not share any common letters (p<0.05).

As Table 4.1 demonstrates, increasing vertical FOV (from 5 to 40 degrees) induces shorter OnsetTime_Including and higher rating significantly for almost every pair. In order to investigate a possibility of linear relation between vertical FOV and vection measures, regression analyses have been conducted as shown in Figure 4.4. and 4.5. Although the regression models are statistically significant (both p<0.0001), their capabilities to explain the variation in vection measures are not good as R-Square values are 0.0856 and 0.1525 for OnsetTime_Including and Rating respectively.

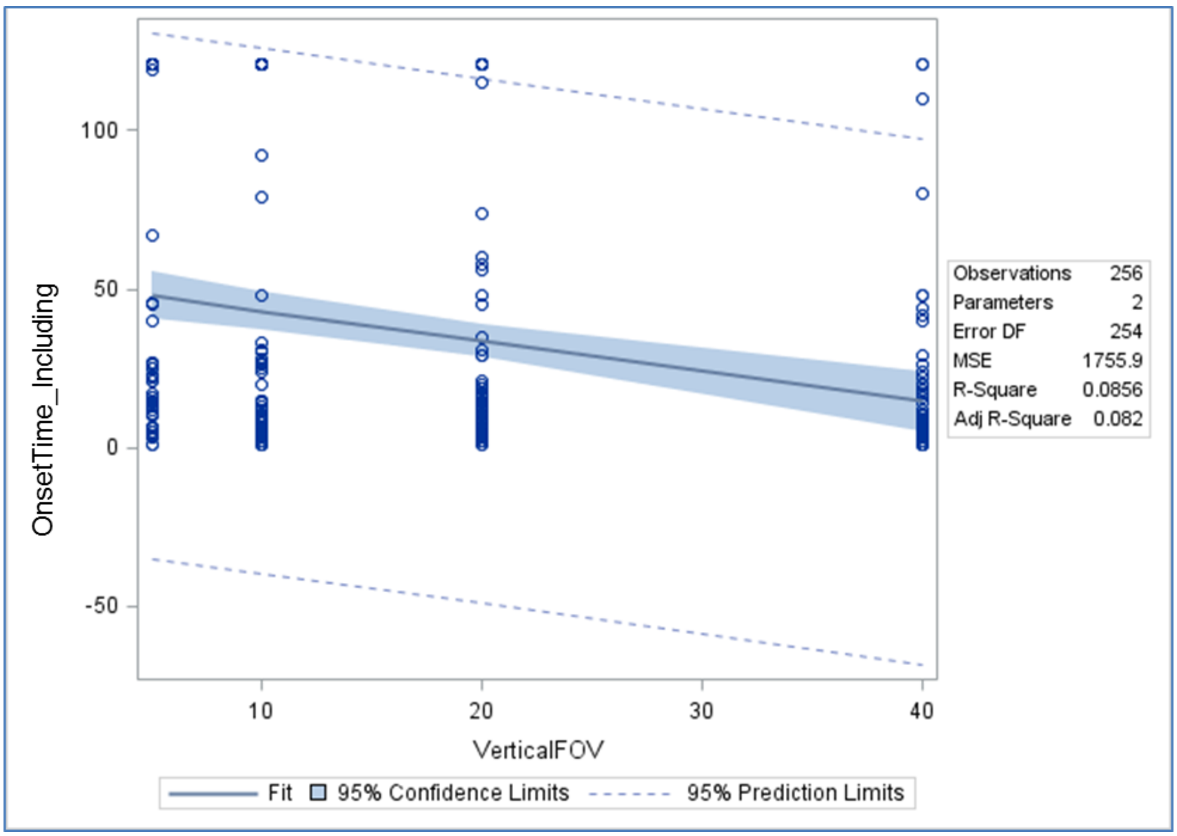

Figure 4.4: Regression analysis for OnsetTime_Including versus VerticalFOV

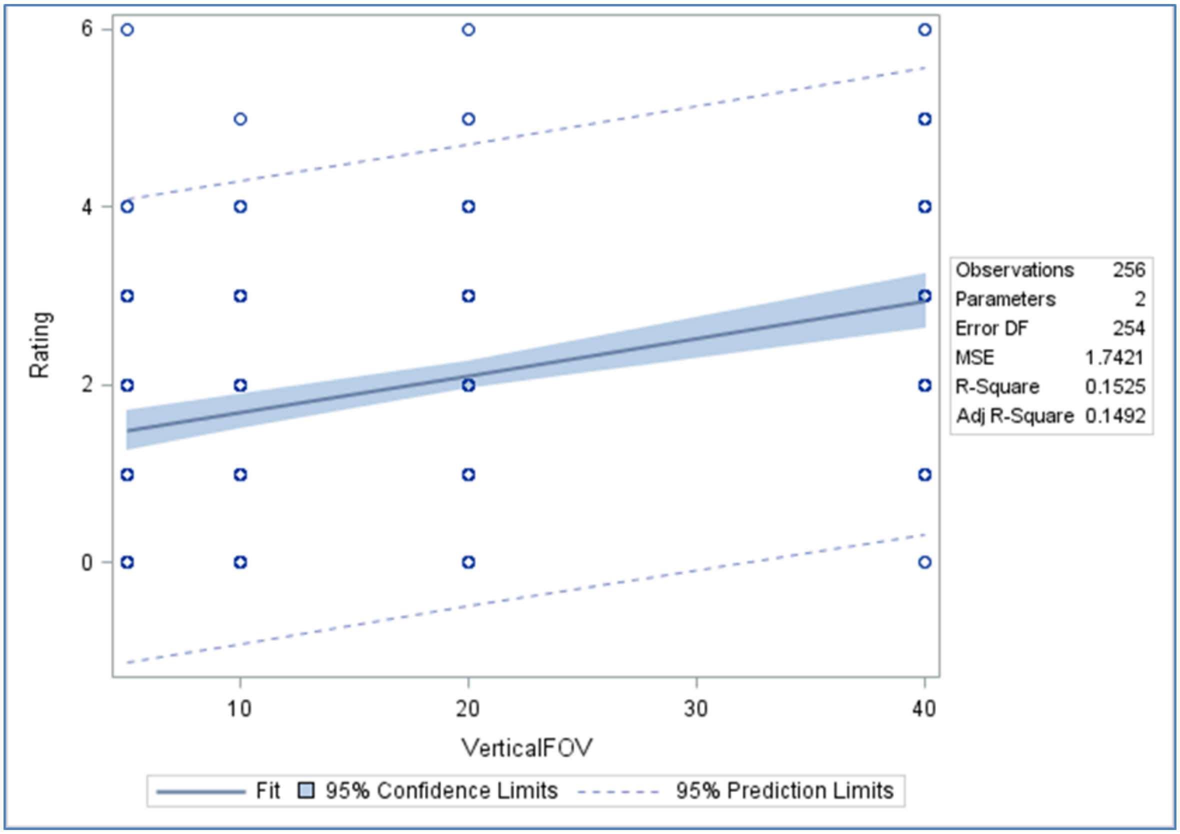

Figure 4.5: Regression analysis for Rating versus VerticalFOV

4.4. Discussion of Experiment 3 (Short-FOV Exp.)

4.4.1. Revisit of the Hypotheses

4.4.1.1. H6: Narrower/shorter FOV causes less compelling vection compared to larger FOV

In Experiment 3, different vertical FOV levels (5, 10, 20, 40 degrees) were tested at a constant horizontal FOV of 1 degree which was located at 70 degrees horizontal location. Although it is still possible to induce vection at 1 degree horizontal by 5 degrees vertical among more than half of the subjects, the general outlook of the results shows that the compellingness of vection reduces from vertical FOV of 40 degree to 5 degree. Therefore, H6 was supported by Experiment 3.

4.4.1.2. H7: Circular vection is more compelling compared to linear vection.

Results of Experiment 3 show that linear stimuli cause more compelling vection than circular stimuli. This result does not support H7 which was formulated based on the results of Trutoiu et al. (2009). The difference between our result and their result may come from the difference of FOV sizes or more probably it may be due to the fact that they analyzed yaw vection versus fore-and-aft whereas we analyzed roll vection versus up-and-down.

This effect can be explained through the subjective vertical theory. The sensed vertical is the gravitational vertical direction that is sensed through "human sense modalities"; whereas subjective vertical is the gravitational vertical direction that is sensed through the "expectations of the central nervous system, based on past interaction with the special environment". (Khalid et al., 2011; Bos et al., 2008)

In our experiments, gravitational force was always parallel to the subject's sagittal plane. Therefore, sensed and subjective verticals were parallel when the stimuli were linear (which makes the vection perception easier); however, they were in conflicting directions when the stimuli were circular (which makes the vection perception more difficult).

4.4.2. Direction of Vection

When the dots on both monitors were going in the same direction, the reported direction of self-motion was always linear and opposite to the direction of dots (except for one trial out of 128 trials).

However, when the dots in one monitor were going up and the dots in the other monitor were going down, the two stimuli induced circular-vection for 66.41% (36.72% being same direction as stimuli; 29.69% being opposite direction to stimuli); linear-vection for 7.03%; no-vection for

26.56% of the trials. As circular vection (66.41%) was reported much more compared to linear vection (7.03%), the stimuli can be regarded as circular although its geometric shape is not a perfect circle.

Furthermore, for the circular stimuli, it has to be noted that same-direction-as-dots (36.72%) was reported more than opposite-direction-to-dots (29.69%). According to vection definition, subjects were supposed to report self-motion in opposite direction to the dots; but not same direction as dots. This contradiction may come from three possible sources: (1) as the stimuli doesn't form a perfect circle shape, the perception of circular vection may be distorted; (2) due to small FOV, subjects' perception of movement is affected; (3) moving white dots might be perceived as background although they only constitute ~10% of the stimuli screen.

4.4.3. Importance of Experiment 1, 2, 3; and Proposal of a Theory: the Connection Theory

In Experiment 3, 13 out of 16 subjects experienced vection with two narrow (1 degree width) and short (5 degrees height) upwardly moving random dot patterns. To the best of our knowledge, this is the first report of vection perception with visual motion of such a small FOV (1 degree x 5 degrees).

It is a very interesting and important finding that stimulation of such a small area on the retina results in vection. When we are observing an environment which is rich in visual cues, such stimulation does not cause as compelling vection as when it is in the darkness; or when the frontal vision is blocked with a cardboard (see Experiment 1 and 2). Blocking the central vision facilitates observer to assume that the environment behind the cardboard is moving too. Similarly, keeping the ceiling light off reduces the amount of visual location cues available to the subject; which makes it easier for the subject to assume that he/she is inside a cabin/capsule and the entire outside-environment is moving although he/she can't see it the full picture of the outside-environment. In other words, we suspect that the observer perceives the stimuli screen as a small window between him/her and an outside-environment. That's why even a FOV of 1x5 degree at each side of the subject can let subject perceive he/she is moving. These arguments made us believe that viewers extrapolate such small FOV to larger FOVs in their mind resulting in an imaginary movement of the entire outside-environment (or self-movement with respect to that large outside-environment).

Moreover, when the dots on one side go down and dots on the other side go up, subjects report circular vection. It means that the subject connects the two stimuli in his/her mind; and perceives them as a one-single-environment. The subject interpolates the two stimuli and composes an imaginary huge stimulus in his/her mind spanning the area between the two stimuli.

When a person looks at an object, say a chair, the edges and visual frame of the chair is sketched in the visual system of the observer; and it is filled in with color and texture. In other words, human perceives the visual images like a cartoon sketch (Ramachandran, 1992). If information of certain parts of the real image is missing, human can fill in them. The visual association cortex, which is responsible for object perception and visual scene completeness, may require subject to perceive that the background environment that is seen through the two small windows constitute a single visual scene that moves together.

This is our explanation on how such small FOVs can induce vection; and we named it the Connection Theory. Further details will be elaborated in the future chapters.

4.4.4. Effects of Horizontal Location Need to be Analyzed

In Experiment 3, the two 1 degree x 5 degrees visual motion strips were placed about 140 degrees apart or at the 70 degrees horizontal locations (see Figure 3.1 in Chapter 3). In order to explore the effects of placing the two stripes at other locations, Experiment 4 was conducted.

CHAPTER 5: EXPERIMENT 4: EFFECTS OF STIMULI LOCATIONS ON VECTION PERCEPTION

5.1. Introduction to Experiment 4

In this chapter, methods and results of Experiment 4 will be discussed. In Experiment 4, we tested the effects of horizontal location of positioning the narrow visual motion stripes (long and short) on vection. Hence, Experiment 4 was also referred to as the Horizontal-location Exp. In Experiments 1 to 3, the visual motion stripes were placed at the 70 degree horizontal position on the left and right side of the peripheral visual fields. For the first time, two stripes of moving random dots (1 degree x 5 degrees) were able to trigger vection sensations in 80% of the viewers. The objective of this experiment was to examine whether the horizontal positions of the two stripes will affect the perceived vection among the viewers. We have formulated Hypothesis 8: Two stripes of 1x5 degree (or 1x40 degree) stimuli located at each side of a viewer can cause vection at different location of the peripheral vision other than 70 degree horizontal location.

5.2. Methods of Experiment 4 (Horizontal-location Exp.)

5.2.1. Subjects of Experiment 4 (Horizontal-location Exp.)

16 self-reported healthy subjects (12 male) were recruited into the Experiment 4. The age of the subjects ranged from 18 to 31 years with a mean of 22.75 and median of 23 years. All of the subjects were tested to have normal or corrected to normal vision according to 20/20 protocol. After the experiment procedure was introduced, all subjects gave a written consent knowing that they can withdraw anytime from the experiment upon their request.

5.2.2. Setup and Procedure of Experiment 4 (Horizontal-location Exp.)

Similar to Experiment 3, ceiling light was kept off and the cardboard is fixed in front of the subjects because these conditions were found more compelling in Experiment 1 and 2. Following the procedure of Experiment 3, each session of Experiment 4 also started with an eye adaptation period of 20 minutes resting after the ceiling light was turned off.

The same setup and procedure as Experiment 3 were used in Experiment 4 (with below exceptions).

Other than 70 degree horizontal location, monitors were positioned at 30 and 45 degrees horizontal locations as well. Moreover, only the shortest (5 degrees) and largest (40 degrees) vertical FOV of Experiment 3 were used in Experiment 4.

5.2.3. Design of Experiment 4 (Horizontal-location Exp.)

Independent variables of Experiment 4 are horizontal location (30, 45, 70 degree), vertical FOV (5, 40 degree), and stimuli direction (upward, downward, clockwise, anti-clockwise). It has to be noted again that vection type (i.e. circular type and linear type) is an intrinsic factor of stimuli direction as clockwise and anti-clockwise are circular; whereas upward and downward are linear.

The factors that are fixed at a level and not changed during the experiment are horizontal FOV (1 degree width), Ceiling Light (off), Frontal Occultation (fixing cardboard in front of the subject), stimuli speed (20cm/s which is approximately 24deg/s).

Vection was measured in the same way as previous three experiments (i.e. OnsetTime_Including, OnsetTime_Excluding, and Rating).

5.3. Results of Experiment 4 (Horizontal-location Exp.)

5.3.1. Main Effects of Vection Type: Linear vs Circular

Similar to the results of previous experiment, compared to circular stimuli, linear stimuli causes significantly shorter OnsetTime_Including ($p<0.0001$; Wilcoxon Signed-Rank Test), and significantly higher vection ratings ($p<0.0001$; Wilcoxon Signed-Rank Test). However, the difference between linear and circular was not significant for OnsetTime_Excluding ($p>0.05$; Mann-Whitney U Test). (See Figure 5.1)

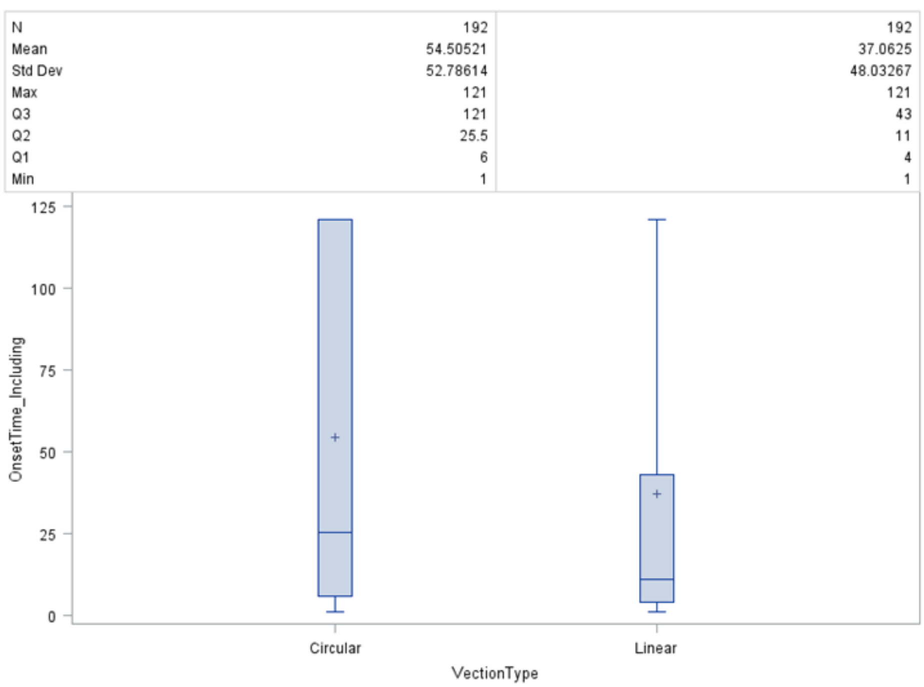

Figure 5.1.a: Main Effects of Vection Type in Experiment 4 on Onset time including no-vection cases

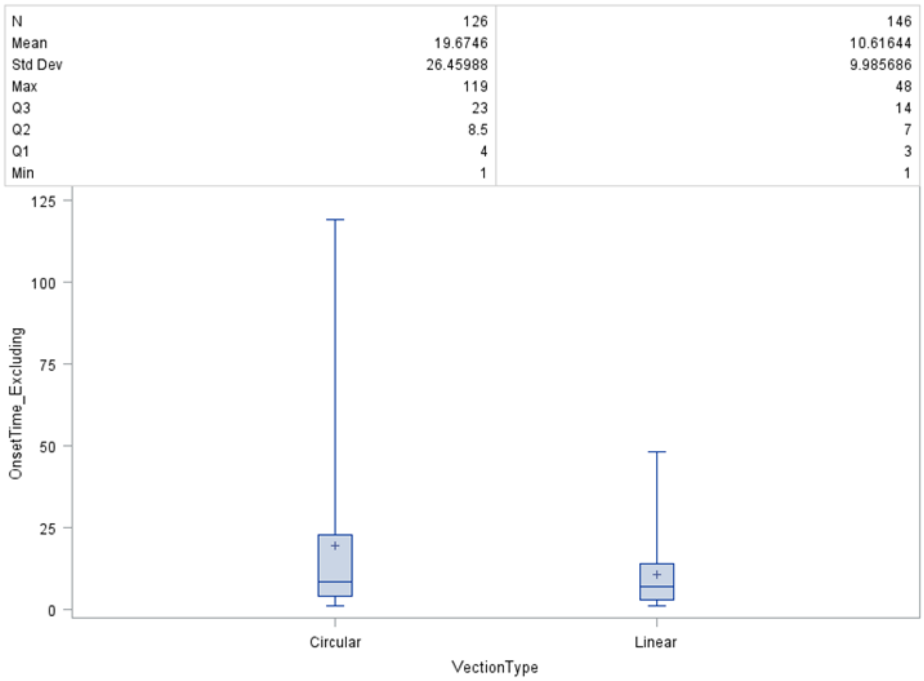

Figure 5.1.b: Main Effects of Vection Type in Experiment 4 on Onset time excluding no-vection cases

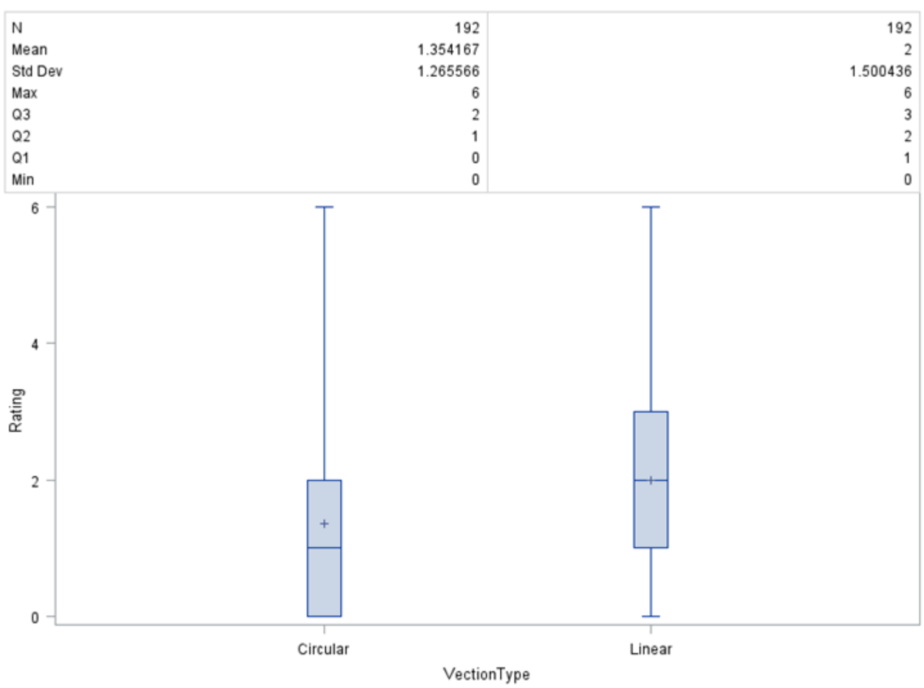

Figure 5.1.c: Main Effects of Vection Type in Experiment 4 on Onset time excluding no-vection cases

5.3.2. Main Effects of Stimuli Direction

Although linear type is more compelling than circular type stimuli, there is no significant difference between neither upward versus downward; nor clockwise versus anti-clockwise for any of the vection measures, i.e. OnsetTime_Including (Wilcoxon Signed-Rank Test), OnsetTime_Excluding (Mann-Whitney U Test), Rating (Wilcoxon Signed-Rank Test) ($p>0.05$). This is parallel in what we have found in the previous experiment. (See Figure 5.2)

N	96	96	96	96
Mean	53.11458	55.89583	36.86458	37.26042
Std Dev	52.4663	53.34288	48.23596	48.08091
Max	121	121	121	121
Q3	121	121	37.5	47.5
Q2	23.5	29.5	11	12.5
Q1	6	5	4	4.5
Min	1	1	1	1

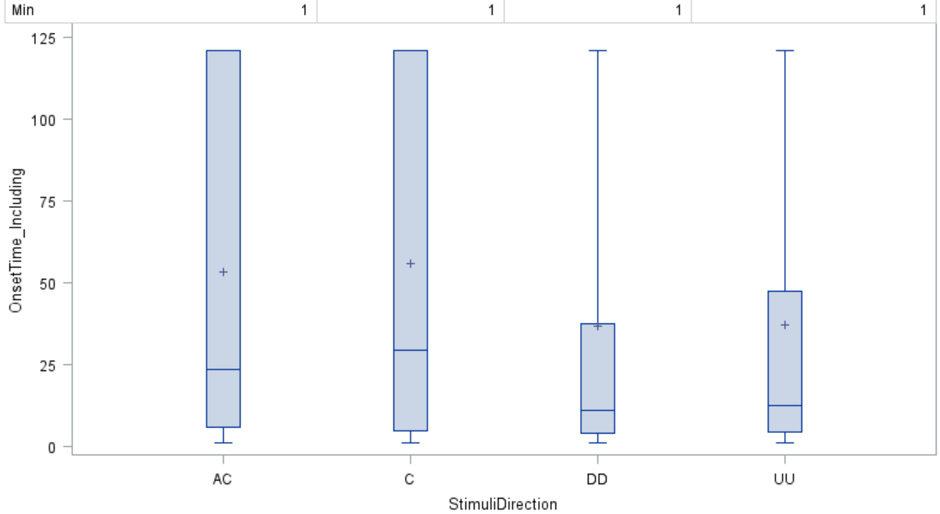

Figure 5.2.a: Main Effects of Stimuli Direction in Experiment 4 on Onset time including no-vection cases

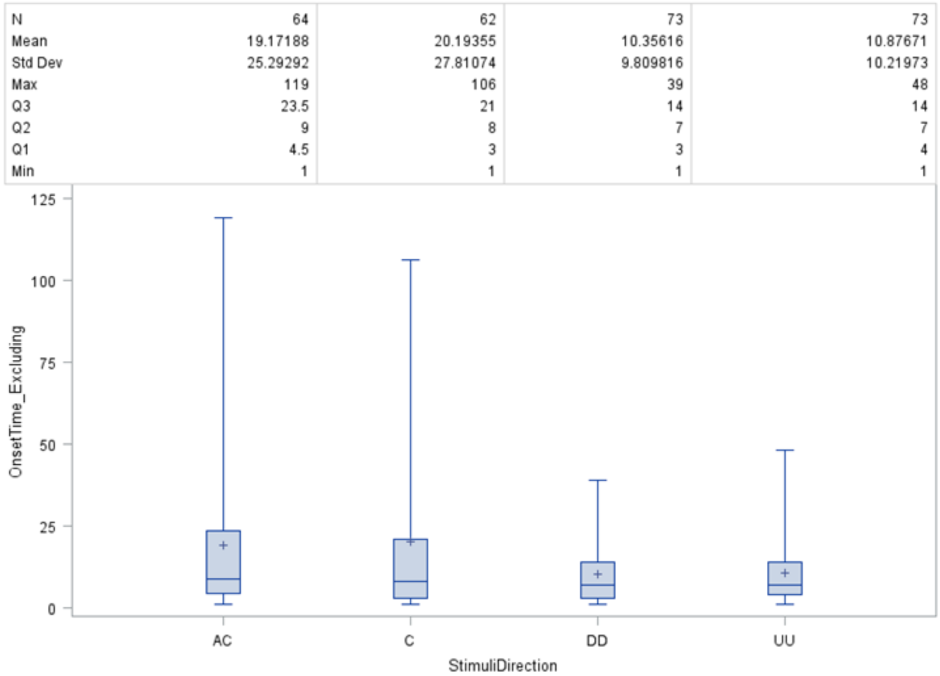

Figure 5.2.b: Main Effects of Stimuli Direction in Experiment 4 on Onset time excluding no-vection cases

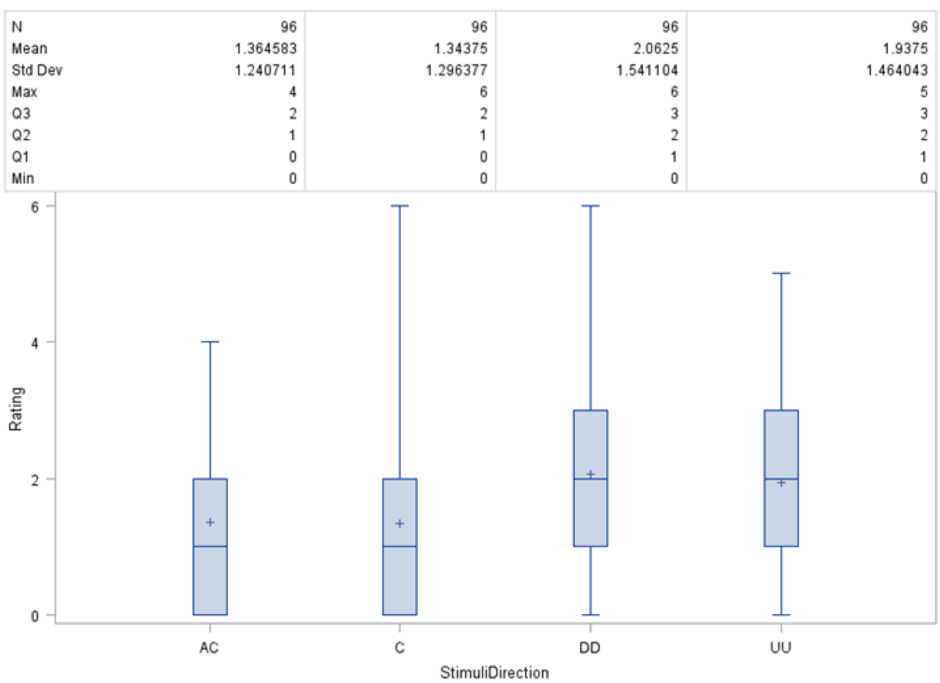

Figure 5.2.c: Main Effects of Stimuli Direction in Experiment 4 on Rating

5.3.3. Main Effects of Vertical FOV

Similar to the results of previous experiment, compared to 5 degrees vertical FOV, 40 degrees vertical FOV causes significantly shorter OnsetTime_Including ($p<0.0001$; Wilcoxon Signed-Rank Test), and significantly higher vection ratings ($p<0.0001$; Wilcoxon Signed-Rank Test). However, the difference between 5 degree and 40 degrees was not significant for OnsetTime_Excluding ($p>0.05$; Mann-Whitney U Test). (See Figure 5.3)

N	192	192
Mean	60.90104	30.66667
Std Dev	54.15912	43.05547
Max	121	121
Q3	121	30
Q2	32	9
Q1	8	4
Min	1	1

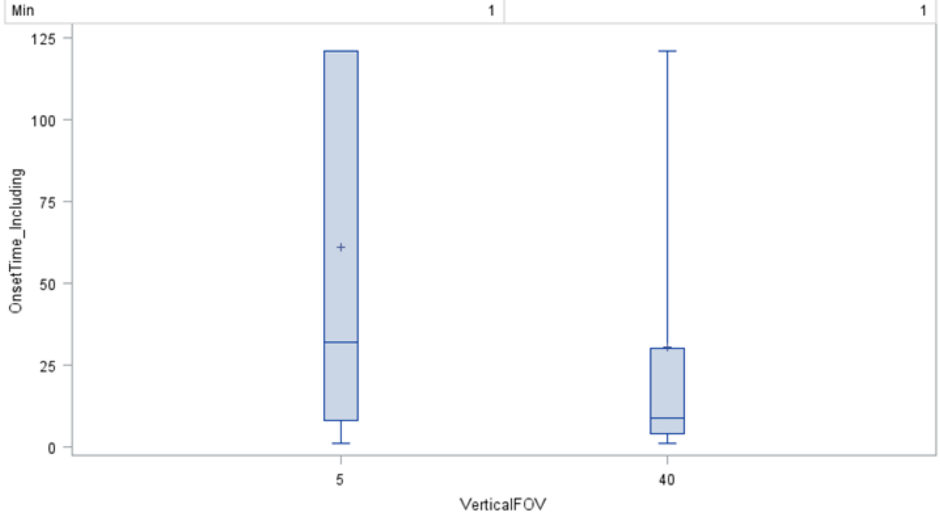

Figure 5.3.a: Main Effects of Vertical FOV in Experiment 4 on Onset time including no-vection cases

	5	40
N	110	162
Mean	16.1	13.93827
Std Dev	19.92737	19.92741
Max	119	114
Q3	19	14
Q2	9.5	6
Q1	4	3
Min	1	1

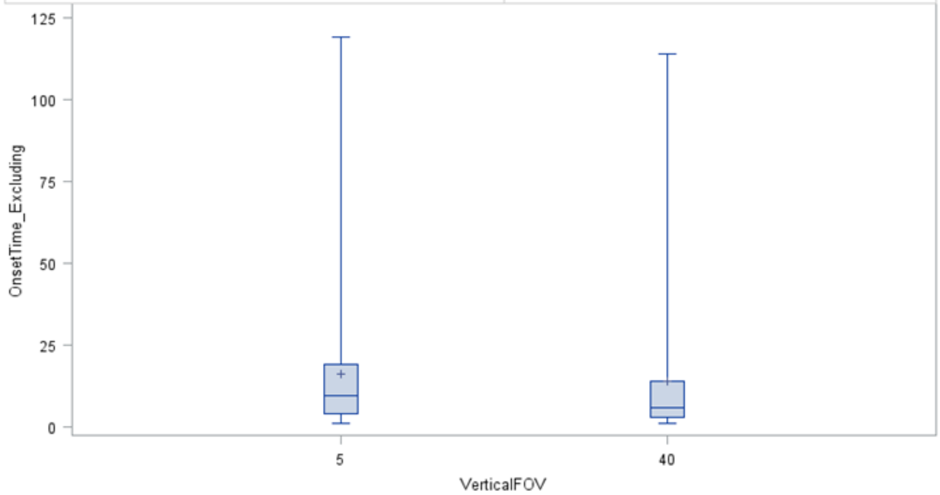

Figure 5.3.b: Main Effects of Vertical FOV in Experiment 4 on Onset time excluding no-vection cases

	5	40
N	192	192
Mean	1.104167	2.25
Std Dev	1.240496	1.365238
Max	5	6
Q3	2	3
Q2	1	3
Q1	0	1
Min	0	0

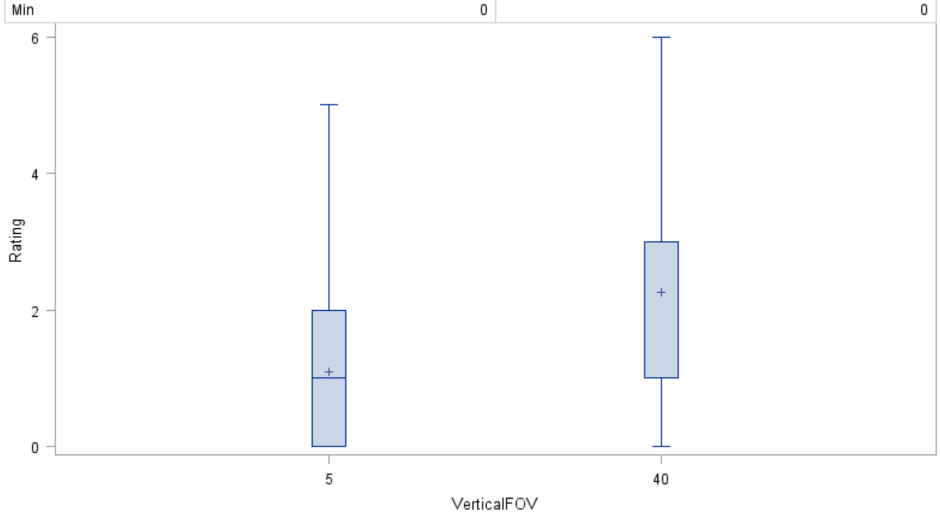

Figure 5.3.c: Main Effects of Vertical FOV in Experiment 4 on Rating

5.3.4. Main Effects of Horizontal Location

Horizontal location of 30, 45 and 70 degrees do not result in significantly different OnsetTime_Including ($p>0.1$; Friedman Test), OnsetTime_Excluding ($p>0.1$; Kruskal-Wallis Test) and Rating ($p>0.1$; Friedman Test). (See Figure 5.4)

In order to consolidate the results of Friedman Test and Kruskal-Wallis Test, each pair (i.e. 30-45, 30-70, and 45-70) was compared by Wilcoxon-Signed Rank Test (for OnsetTime_Including and Rating) and Mann-Whitney U Test (for OnsetTime_Excluding). Except for the Ratings of 45-70 ($p<0.05$; Wilcoxon Signed-Rank Test), no pair showed significant difference for any of the vection measures ($p>0.05$).

N	128	128	128
Mean	47.17969	46.16406	44.00781
Std Dev	51.48219	52.21062	50.08646
Max	121	121	121
Q3	121	121	121
Q2	16	11.5	14.5
Q1	5	4	5
Min	1	1	1

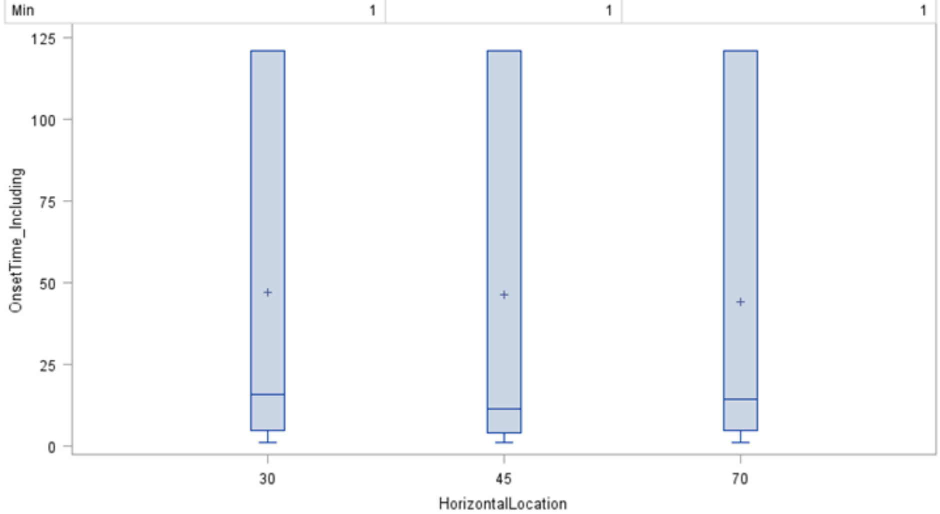

Figure 5.4.a: Main Effects of Horizontal Location in Experiment 4 on Onset time including no-vection cases

N	89	91	92
Mean	14.83146	15.73626	13.88043
Std Dev	18.75211	24.65938	15.43995
Max	106	119	89
Q3	17	14	18
Q2	9	6	9
Q1	4	3	4
Min	1	1	1

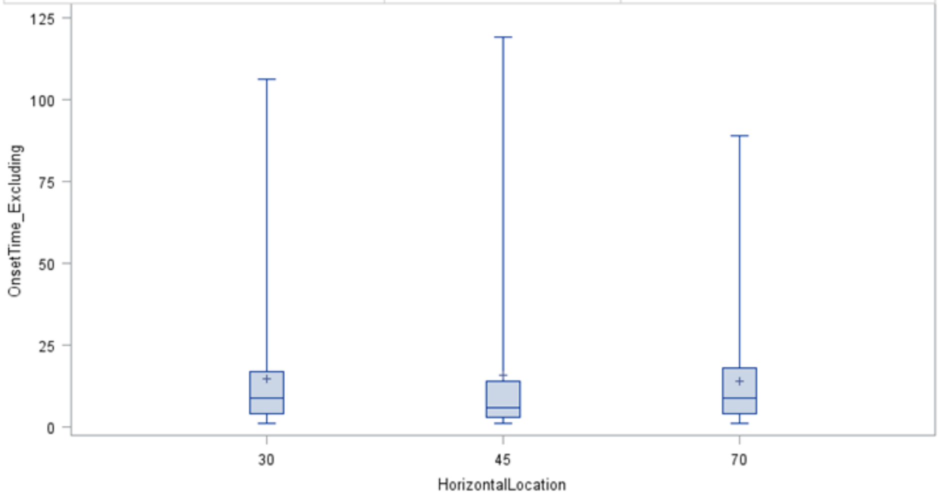

Figure 5.4.b: Main Effects of Horizontal Location in Experiment 4 on Onset time excluding no-vection cases

N	128	128	128
Mean	1.65625	1.578125	1.796875
Std Dev	1.48715	1.366698	1.416213
Max	5	6	6
Q3	3	3	3
Q2	1	1	2
Q1	0	0	0
Min	0	0	0

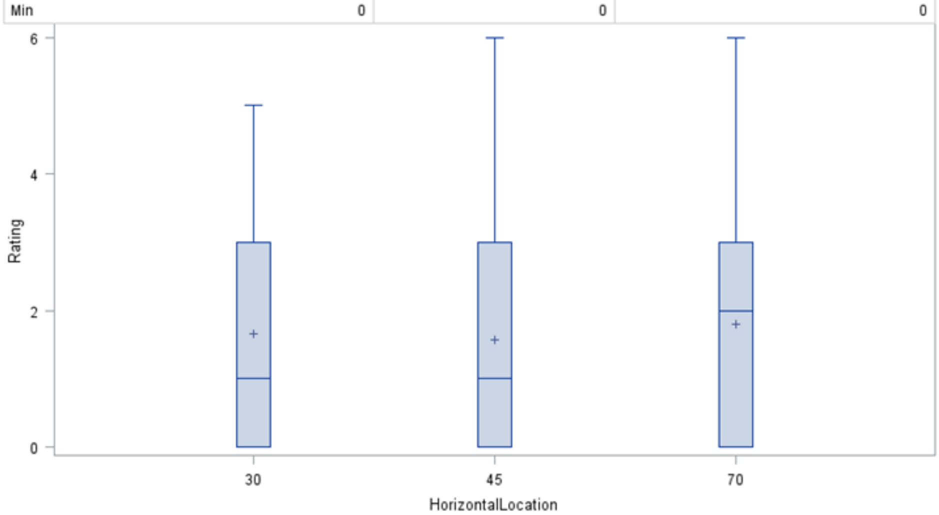

Figure 5.4.c: Main Effects of Horizontal Location in Experiment 4 on Rating

5.4. Discussion of Experiment 4 (Horizontal-location Exp.)

5.4.1. Revisit of hypotheses

The hypothesis H8 states that the two stripes of 1x5 degree (or 1x40 degree) stimuli located at each side of a viewer can cause vection at different locations of the peripheral vision other than 70 degree horizontal location. As found in Experiment 4, vection was reported in all three horizontal location conditions (30, 45 and 70 degrees). Therefore, findings of Experiment 4 support H8.

5.4.2. More on the Connection Theory

As discussed in Chapter 4, we suppose that viewers connect the two stimuli in their minds and assume that they are parts of the same outside-surrounding-environment. Therefore, if what they saw from the two stripes were window views of a larger moving surrounding, viewers may assume that the places where they were seating were moving or they were moving relative to their surrounding environment.

By connecting the two stimuli in mind, we do not only mean interpolation of the two stimuli, but also extrapolation of them. For example, when the two stimuli are placed at 30 degree horizontal location, they span approximately 60 degree horizontal FOV in front of the subject; whereas 70 degree horizontal location spans approximately 140 degree horizontal FOV. We already proved that larger FOV causes more compelling vection (in Experiment 3 and 4). Therefore, if there were only interpolation of the two stimuli, 70 degree horizontal location would cause more compelling vection than 30 degree horizontal location because of the area spanned after interpolation. However, as the results of Experiment 4 showed, there is no significant difference in vection measure of 30 degree and 70 degree horizontal locations. The interpolation alone is not enough to explain this effect. Therefore, we have to accept that subject not only interpolates but also extrapolates the stimuli to a larger moving outer-environment. In this way, we can explain why 30 degree horizontal location is not different than 70 degree horizontal location because they carry same amount of information about the outer-environment as long as their FOV are same too.

Before experiments started, subjects saw the experimental setup; and they were aware of the fact that only the dots in the monitors would be moving throughout the experiment but not their chair. According to Riecke (2009), possibility of real physical movement increases vection. Therefore, it has to be noted that our vection ratings can be increased and onset times can be decreased if the subjects are placed in an environment where the possibility of real physical self-motion exists.

5.4.3. Filling-in Effects on the Blind Spot and the Connection Theory

Our eyes have a blind spot where the optic nerve leaves the eye. It is called blind spot because it does not have ocular receptors. Although monocular vision cannot directly perceive the color and texture at the location corresponding to the blind spot, human can perceptually fill-in the area corresponding to the blind spot, based on the information coming from the surrounding environment. (Spillmann et al., 2006; Zur and Ullman, 2003; Ramachandran, 1992)

Ramachandran (1992) demonstrated that the filling-in effect at the blind spot is applicable to patients who suffer from scotoma (i.e. an area in retina that does not have functioning receptors) at central vision as well. When people who have scotoma look at a uniform wallpaper, they see a continuous pattern without being disrupted by their scotoma. When another object is placed at the location corresponding to their scotoma, they cannot see the object; instead they only perceive the uniform wall alone due to the filling-in effect.

The filling-in effect at the blind spot and scotomas proves that human can interpolate the missing information based on the surrounding information available. Therefore, filling-in effect is not imagining or hallucinating; instead it is perception or illusion (if the filling-in is done mistakenly). Zur and Ullman (2003) demonstrated that the filling-in effect can be valid for an area as large as a disc with diameter of 14 degrees at the central vision. Compared to 14 degrees, the gap we had in our experiments (i.e. up to around 140 degrees horizontal FOV) is quite big which cannot be filled in perfectly. However, our subjects might use imagination and help of real filling-in effect to some extent to perceive compelling vection.

5.4.4. Testing the Connection Theory

Based on the results of our experiments, we came up with the Connection Theory. However, we are still not 100% sure if it is really a valid theory that can be applied to explain other situations in vection at small FOVs. Therefore, in the Experiment 5 and Experiment 6 we formulated some hypotheses to test and explore the Connection Theory.

CHAPTER 6: EXPERIMENT 5: CLOSING ONE EYE AFTER PERCEIVING CIRCULAR VECTION WITH TWO EYES

6.1. Introduction to Experiment 5

In Experiment 3 and 4, we found out that when the dots on one narrow stripe go down while the dots on the other stripe go up, subjects report circular vection. According to the hypothetical prediction of the proposed Connection Theory, the viewers “connect” the two moving stripes to form a whole rotating surrounding. In Experiment 5, we wanted to test this hypothesis.

If viewers feel circular vection for two stripes at each side, the proposed Connection Theory claims that the viewers are assuming that the entire environment is moving and the moving dot patterns are just part of that moving environment. If this is true, after the viewers believed that the entire environment is moving, closing one of their eyes wouldn’t stop the illusionary sensation of circular self-motion immediately. Although after closing one eye they will only perceive a linear (say upward) stimuli on one side alone, if they really connect these two stimuli together as part of the larger and rotating environment, closing one eye and not being able to see the other window view should not stop the circular vection immediately.

After closing one eye and observing the only one stimulus for a long time may make viewers’ mind change to perception of linear vection. However, if the connection theory is true this change of mind shouldn’t be instant because the rest of the environment that they cannot see (i.e. the environment that is blocked by cardboard) is still rotating in their minds. Therefore, Experiment 5 was also referred as the Mono-Exp.

Based on these arguments, the Hypothesis 9 was formulated as H9: After perceiving circular vection for two stripes located at each side, closing one eye doesn't stop circular vection immediately.

6.2. Methods of Experiment 5 (Mono-Exp.)

6.2.1. Subjects of Experiment 5 (Mono-Exp.)

16 self-reported healthy subjects (13 male) were recruited into the Experiment 5. The age of the subjects ranged from 18 to 31 years with a mean of 23.1 and median of 23 years. All of the subjects were tested to have normal or corrected to normal vision according to 20/20 protocol. After the experiment procedure was introduced, all subjects gave a written consent knowing that they can withdraw anytime from the experiment upon their request.

6.2.2. Setup and Procedure of Experiment 5 (Mono-Exp.)

Similar to Experiment 3 and 4, ceiling light was kept off during Experiment 5; and each session of Experiment 5 also started with an eye adaptation period of 20 minutes resting after the ceiling light was turned off.

The same monitors and computer program as Experiment 3 and 4 were used in Experiment 5. The two monitors were positioned at 70 degree horizontal location.

In this experiment, we preferred asking subjects to close one of their eyes instead of shutting down one monitor. The reason behind this is that when subject closes one eye, he/she still knows or assumes that the stimuli that he/she cannot see anymore is still probably continuing its movement. However, shutting down one of the monitors while both eyes of the subject are open lets subject see that it's not moving anymore. In other words, absence of evidence (i.e. closing one eye) is not same as evidence of absence (i.e. seeing the monitor that is shut down).

Addition to the setup of the previous experiments, a new computer program was developed for inputting the ending time of circular vection. Subject used “S” and “I” buttons on a keyboard to control that program. In order to increase accuracy and facilitate data collection, all the irrelevant keys, i.e. except for “S” and “I”, were removed from the keyboard.

Before each trial started, subjects were verbally informed that the stimuli would come soon; and subjects pressed “S” button to confirm that they were ready for the trial both eyes open keeping their heads on the chin rest. They were allowed to see the stimuli with two eye for utmost 120 seconds. If they didn’t report vection within 120 seconds, the trial was stopped and experiment moved to another trial. If they reported vection, their subjective ratings, onset time, and vection direction were recorded verbally telling which eye to be closed soon as well; and they were allowed to focus on the stimuli back to feel sensation of self-motion to the highest possible extent. When they feel ready; they closed one of their eyes (both with means of eyelid and a hand), and pressed “I” button at the same time. When their sensation of circular motion stopped (or changed into linear motion), they pressed the “I” button again. The computer program calculated the time between two presses of “I” button, which is equal to the ending time of circular vection after closing one eye (i.e. EndingTimeOfCircularVection).

Each subject completed a total of 8 trials (2x2x2) (i.e. closing right eye / left eye, type of starting stimuli linear / circular, direction of stimuli)

In order to give subjects more space to use the data collecting keyboard, eye occluding cardboard was replaced with a larger one that was placed further.

The focus of Experiment 5 was on ending time of circular vection after closing one eye, which will be spelled as EndingTimeOfCircularVection from now on.

The factors that are fixed at a level and not changed during the experiment are horizontal location (70 degrees), horizontal FOV (1 degree width), vertical FOV (40 degrees), Ceiling Light (off), eye occultation (fixing cardboard in front of the subject), stimuli speed (20cm/s which is approximately 24deg/s).

6.3. Results of Experiment 5 (Mono-Exp.)

Although 16 subjects completed Experiment 5, two of them reported linear or no-vection for the circular stimuli when their both eyes were open. Therefore, we have the data of 14 subjects for EndingTimeOfCircularVection after closing one eye. As each subject had 4 circular trials, there is a total of 56 data points of EndingTimeOfCircularVection. In Table 6.1, averages of EndingTimeOfCircularVection of 4 trials of each subject are presented.

Subject No	**EndingTimeOfCircularVection (Average of 4 trials) (sec)**
1	12.01
2	3.74
3	1.49
4	2.75
6	16.08
7	11.79
8	0.79
9	3.02
10	1.97
11	23.96
12	1.31
13	10.32
14	5.37
15	3.78
Overall Average:	**7.03**

Table 6.1: Average EndingTimeOfCircularVection of 4 trials of each subject who reported circular vection. (Subject No 5 and 16 are not shown in the above table because they reported linear or no-vection for the circular stimuli when their both eyes were open.)

Mean of the EndingTimeOfCircularVection is 7.03sec, and median of it is 4.12sec. Wilcoxon Signed-Rank Test and Student's t-test showed that the mean of EndingTimeOfCircularVection is significantly different than zero ($p<0.0001$).

A correlation analysis showed that EndingTimeOfCircularVection is not significantly correlated to OnsetTime or Rating recorded when both eyes are open ($p>0.05$). However, it has to be noted that the p-value for the correlation between EndingTimeOfCircularVection and Rating was 0.0911 which may represent a marginally significant correlation between the two factors.

A comparison of subjects who have low tendency to maintain circular vection (i.e. Average of four trials < 5sec) versus subjects who have high tendency to maintain circular vection after closing one eye (i.e. Average of four trials > 5sec) was also performed. Mann-Whitney U Test was applied to compare these two groups; and found that EndingTimeOfCircularVection of high-tendency-group is significantly longer than low-tendency-group ($p<0.0001$).

6.4. Discussion of Experiment 5 (Mono-Exp.)

Hypothesis 9 was supported by Experiment 5 as the mean EndingTimeOfCircularVection was found to be greater than zero.

When subjects were asked to close their both eyes together, vection stopped immediately. However, when they close only one eye their circular vection needs some time to stop or change into linear one.

When the initial stimulation of two eyes was with linear stimuli, closing one eye didn't result in circular vection.

The above findings support the Connection Theory and can be used for enhancing it. Once a viewer connects two stimuli to form an outer-environment, the link between two stimuli doesn't immediately disappear even if one of the stimuli disappears from the sight.

CHAPTER 7: EXPERIMENT 6: VECTION AT CENTRAL VISION

7.1. Introduction to Experiment 6

In Experiment 4 stimuli were located at 30, 45, and 70 degree horizontal locations; and in the other Experiments (i.e. 1,2,3,5), stimuli were at 70 degree horizontal location. In Experiment 6, we wanted to discover if it is possible to induce vection at central vision. Johansson (1977) claimed that no vection was reported at central vision in his study which was conducted under normal lighting. We have already found that keeping the ceiling light off increases chance of vection to occur; and our pilot testing showed that it may be possible to induce vection at central vision as well. Therefore, Hypothesis 10 (H10) was formulated as: Vection can be induced at central vision as well.

In Experiment 6, we wanted to explore more about the hypothetical prediction of Connection Theory. As we learnt from Experiments 3-5, when the dots on one stripe go down and the dots on other stripe go up; most of the subjects reported circular vection. When two long stripes (40 degrees) are at the peripheral vision, it is easy to connect them to constitute a circular motion. However, when the two long stripes are placed closely at the central vision, their shapes and geometry do not represent two natural partial views of a rotating scene in the physical world. This may make it difficult for viewers to connect the two stimuli. We believe that if the height of stripes is not too long (i.e. 5 degrees), they may be perceived as tangent lines of a circle. Therefore, we formulated Hypothesis 11 (H11) as: Two long stripes (i.e. 40 degrees) going in opposite directions do not induce more compelling vection than two short stripes (i.e. 5 degrees) when they are placed very close to each other and nearer to the central vision. Consequently, Experiment Six was also referred to as the Central-Vision Exp.

7.2. Methods of Experiment 6 (Central-vision Exp.)

7.2.1. Subjects of Experiment 6 (Central-vision Exp.)

17 self-reported healthy subjects (13 male) were recruited into the Experiment 6. The age of the subjects ranged from 18 to 31 years with a mean of 23.4 and median of 23 years. All of the subjects were tested to have normal or corrected to normal vision according to 20/20 protocol. After the experiment procedure was introduced, all subjects gave a written consent knowing that they can withdraw anytime from the experiment upon their request.

16 out of 17 subjects of Experiment 6 have taken part in Experiment 5 as well.

7.2.2. Setup and Procedure of Experiment 6 (Central-vision Exp.)

Similar to Experiment 3-5, ceiling light was kept off during Experiment 6; and each session of Experiment 6 also started with an eye adaptation period of at least 20 minutes after the ceiling light was turned off.

The same monitors and computer program as Experiment 3 and 4 were used. The monitors were placed at the central vision. The entire monitors except for the stimuli area were covered with black color cardboards to reduce the visual cues available to the subject. The peripheral vision was also occluded by means of large cardboards.

The locations of the stimuli in previous experiments were defined in terms of "horizontal location" in the perimetric chart of each eye. 70 degree horizontal location on right/left eye deviates 70 degree from the center of the straight gaze. In other words, two stimuli located at 70 degree horizontal locations span an area of approximately 140 degrees. (See Figure 3.1 and 3.3) However, this approximation is not valid for the central vision because of the inter-pupillary distance between the two eyes of a human. Therefore, the term "horizontal distance" was used to refer the exact locations of stimuli in Experiment 6. (See Figure 7.1)

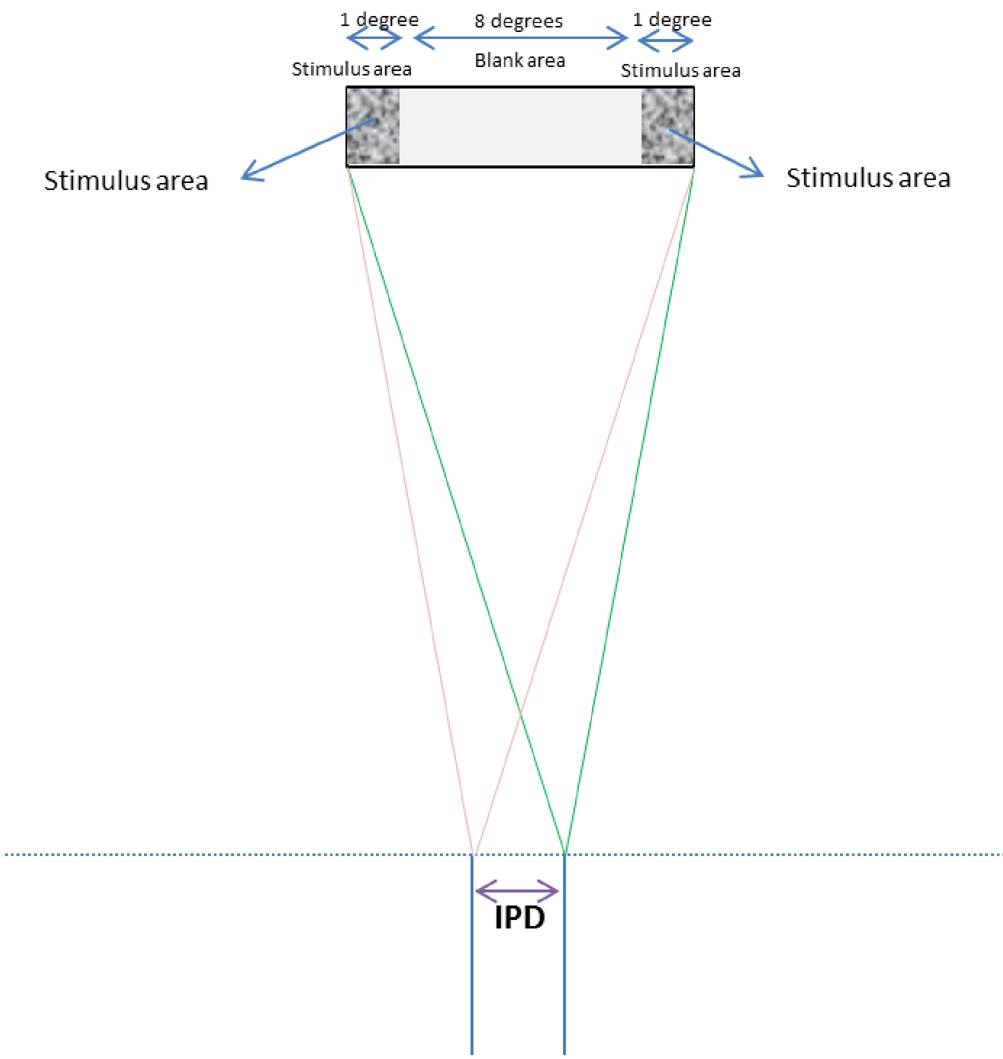

Figure 7.1: Top view of the setup of Experiment 6

Each stimulus covered 1 degree horizontal FOV in each eye. The blank gap between the two stimuli was 8 degrees. Therefore, the two stimuli together spanned an area of 10 degree horizontal FOV in each eye. (See Figure 7.1)

Stimuli direction was fixed in Experiment 6. The dots on left were going downward; and the dots on right were going upward. This direction was chosen for presenting because the percentage of subjects who reported vection for this direction was slightly higher than opposite direction in Experiment 3 and 4.

Each condition was shown to each subject for utmost 120 seconds. If subject hasn't reported any vection, experiment proceeded to the next condition. If subject has reported vection, onset of vection, direction of vection, and subjective rating were recorded.

7.2.3. Design of Experiment 6 (Central-vision Exp.)

Independent variable of Experiment 6 is vertical FOV (5, 10, 40 degrees).

The factors that are fixed at a level and not changed during the experiment are horizontal distance between the two stimuli (8 degrees, covering total of 10 degrees including the two stimuli area), horizontal FOV of each stimulus (1 degree width), Ceiling Light (off), Frontal/Peripheral Occultation (peripheral and central vision were covered with black color cardboard expect for the stimuli areas), stimuli speed (20cm/s which is approximately 24deg/s), stimuli direction (left going down, right going up).

Vection was measured in the same way as Experiment 1-4 (i.e. OnsetTime_Including, OnsetTime_Excluding, and Rating).

7.3. Results of Experiment 6 (Central-vision Exp.)

Main Effects of Vertical FOV at the Central Vision

Vertical FOV doesn't have significant effect on any of the vection measures, i.e. OnsetTime_Including ($p>0.1$; Friedman Test), OnsetTime_Excluding ($p>0.1$; Kruskal-Wallis Test) and Rating ($p>0.1$; Friedman Test). (See Figure 7.2)

Each pair of Vertical FOV (i.e. 5-10, 5-40, 10-40 degrees) was also compared with Wilcoxon-Signed Rank Test (for OnsetTime_Including and Rating) and Mann-Whitney U Test (for OnsetTime_Excluding). No pair showed significant difference for any of the vection measures ($p>0.05$).

	5	10	40
N	17	17	17
Mean	96.11765	99.23529	92.29412
Std Dev	36.32644	36.18275	38.95312
Max	121	121	121
Q3	121	121	121
Q2	121	121	114
Q1	72	90	70
Min	11	24	21

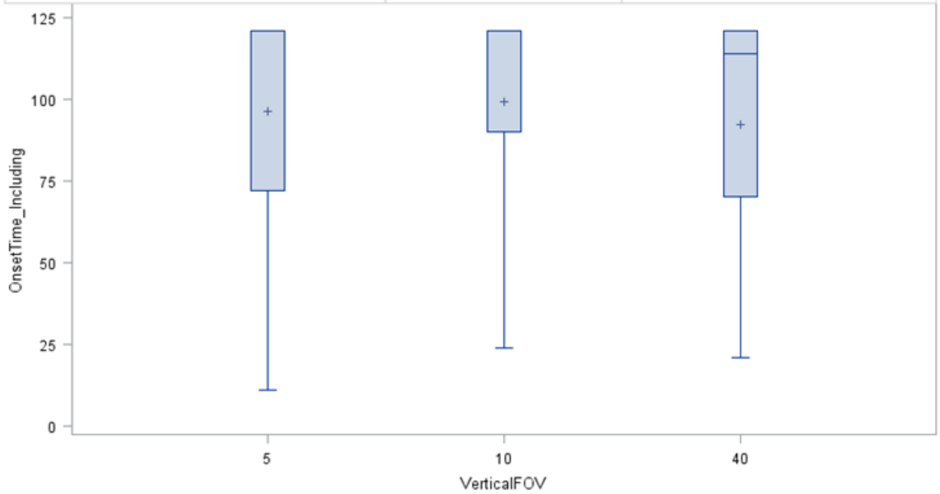

Figure 7.2.a: Main Effects of Vertical FOV in Experiment 6 on Onset time including no-vection cases

	5	10	40
N	7	6	9
Mean	60.57143	59.33333	66.77778
Std Dev	31.82691	35.16627	38.44729
Max	97	114	114
Q3	96	90	109
Q2	62	48	70
Q1	31	32	32
Min	11	24	21

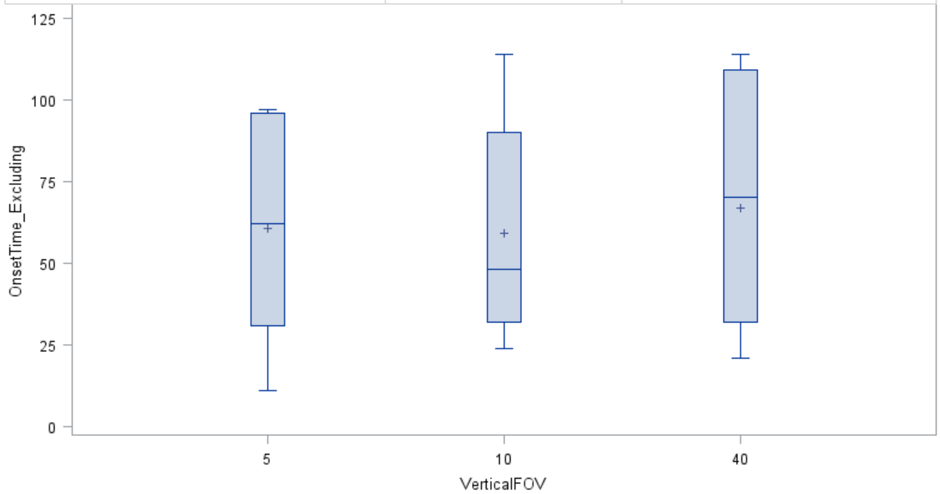

Figure 7.2.b: Main Effects of Vertical FOV in Experiment 6 on Onset time excluding no-vection cases

N	17	17	17
Mean	0.941176	1.176471	1
Std Dev	1.638238	1.911652	1.224745
Max	6	6	4
Q3	1	2	2
Q2	0	0	1
Q1	0	0	0
Min	0	0	0

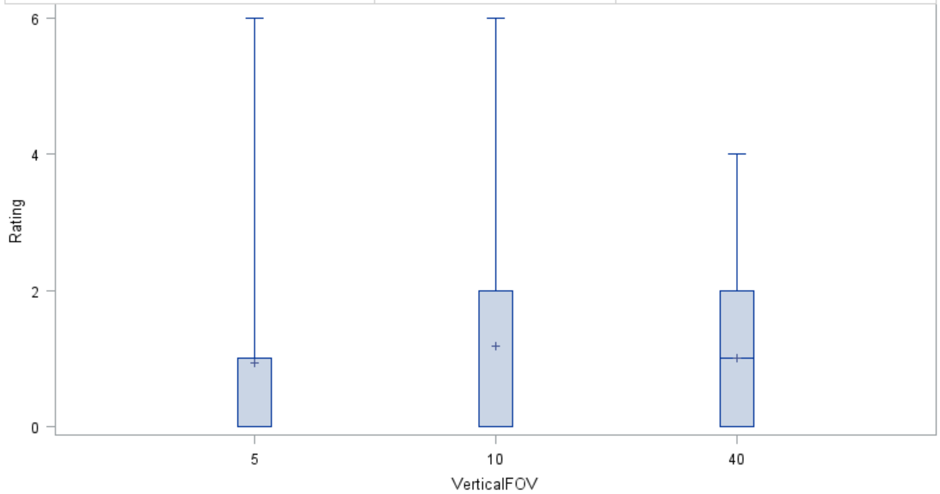

Figure 7.2.c: Main Effects of Vertical FOV in Experiment 6 on Rating

7.4. Discussion of Experiment 6 (Central-Vision Exp.)

In Experiment 5, the two stimuli going in different directions mostly induced circular vection (89.06% of trails resulted in circular vection, 7.81% linear vection, 3.13% no-vection). However, in Experiment 6, such stimuli was placed at the central vision and mostly induced no-vection (56.86% of trials resulted in no-vection, 27.45% circular vection, 15.69% linear vection). (See table 7.1 for breakdown of each Vertical FOV). It shows that subjects felt less connection between the two stimuli as they don't represent a circular shape anymore in Experiment 6. With this finding we can update the connection theory as physical proximity of two stimuli does not necessarily increase the easiness of connecting them together; contextual proximity is also important for connecting them. Moreover, being at peripheral or central vision has to be taken into account.

Vertical FOV	Percentage/number of Circular Vection	Percentage/number of Linear Vection	Percentage/number of No-Vection
5 degrees	5 times	2 times	10 times
10 degrees	3 times	3 times	11 times
40 degrees	6 times	3 times	8 times
Total	14 times reported (27.45%)	8 times reported (15.69%)	29 times reported (56.86%)

Table 7.1: Number/percentage of circular vection and linear vection at each Vertical FOV level in Experiment 6

Rows (Vertical FOV) and columns (Vection Type) of the Table 7.1 was checked with Chi-Square test; and the null hypothesis of homogeneity (i.e. H_0: $P_{1j}=P_{2j}=P_{3j}$) was failed to be rejected. ($p<0.05$) Therefore, we can assume that different vertical FOV values (i.e. 5 degrees, 10 degrees, and 40 degrees) have similar distribution of vection type (i.e. circular vection, linear vection, and no-vection). Although assumptions of Chi-Square test may be violated as not every cell has at least 5 observations, we can still observe the general pattern by just looking at the table without denoting a specific significance level in terms of statistics.

As demonstrated in Table 7.1, 27.45% of trials resulted in circular vection, and 15.69% of them resulted in linear vection. In total, 43.14% of the trials resulted in vection. As the stimuli were at central vision, this result supports Hypothesis 10; i.e. H10: Vection can be induced at central vision as well.

Hypothesis 11 (i.e. H11: Two long stripes (40 degrees) going in opposite directions do not induce more compelling vection than short stripes (5 degrees) when they are placed very close to each other) is also supported by Experiment 6 as found that the effects of different vertical FOVs on vection measures are not significantly different.

In Experiments 3 and 4, we found that longer strip (i.e. 40 degrees) causes more compelling vection than shorter strip (i.e. 5 degrees) when they are located at peripheral vision. The reason for that can be the amount of stimulation viewer received or the amount of information about the outer-environment carried to the viewer. However, in Experiment 6 when the stimuli are located at central vision, the difference of vection measures of long and short stripes disappeared. Even at the central vision amount of stimulation of long strip is more than that of short strip; yet the amount of information about the outer-environment carried to the viewer is an ambiguous topic. When the strips are short, it is easier for viewer to connect them as a rotating circle at the outer-environment which he/she is looking through the so-called window. However, when the strips are long, the stimuli don't match with a rotating disk in the outer-environment that is being viewed through the so-called window. When strips are long, stimuli may be perceived as a chain rotating around a prolate spheroid which is more difficult to imagine compared to a simple circular motion. Therefore, the advantage of large FOV is balanced out with the disadvantage of improper shape when the stimuli are at the central vision which resulted in no significant difference of vection measures at long and short stimuli of Experiment 6.

Another issue that needs to be discussed here is the comparison of central vision and peripheral vision. Johansson (1977) claimed that his stimulation didn't induce any vection at the central vision. He didn't give much descriptions about his experiment at the central vision except for that he placed a monitor of 42cm by 42cm at different distances in front of the subject (which might possibly covered entire central vision in some trials); and he concludes that none of his subjects reported vection when the monitor is at the central vision although majority of his subjects reported vection when it is at the peripheral vision.

However, in our case, we achieved vection at central vision. Here, vection at central and peripheral visions will be compared. Comparing two long stripes at the peripheral and central will have the confounding effect that has been discussed above through the Connection Theory. However, two stripes of 5 degree FOV at central vision and peripheral vision can be compared safely in order to find whether central vision is different than peripheral vision at such small FOVs. In Experiment 6, 41.18% of the subjects reported vection for two stripes of 5 degree FOV (left going down, right going up); but in Experiment 3, this percentage was 56.25% (at 70 degree horizontal location); and in Experiment 4, it was 43.75%, 56.25%, 50.00% (at 30, 45, and 70 degree horizontal locations respectively). Therefore, we can conclude that although it is possible to induce compelling vection at central vision, although percentage of people who reports vection at central vision is not as high as that at peripheral vision.

CHAPTER 8: CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

8.1. Major Findings

In this thesis, vection perception induced by watching narrow stripes of moving dots was investigated through a series of experiments. Stimuli of the experiments consisted of random dot patterns covering small FOVs as small as 1x5 degrees to 1x47degrees. Major findings of the experiments are listed below:

- Keeping ceiling light off, compared to keeping it on, when watching two narrow stripes of moving dots induces significantly more compelling vection with and/or without eye adaption.
- Frontal occultation by means of a cardboard, compared to staring at a fixation point with open view, causes significantly more compelling vection when watching two narrow stripes of moving dots placed on both sides of peripheral visual fields.
- Within the limits of speed levels tested in this experiment (i.e. 4, 8, 16, 21.4 cm/sec), dot patterns moving at higher speeds induce significantly more compelling vection when the ceiling light is off although speed doesn't significantly affect vection measures when the ceiling light is on.
- Upward and downward directions of stimuli induce similar levels of vection measures.
- Clockwise and anticlockwise directions of stimuli induce similar levels of vection measures.
- Linear stimuli (i.e. upward/downward moving dots), compared to circular stimuli (i.e. clockwise/anticlockwise as facilitated by one upward and one downward moving dots patterns) cause significantly more compelling vection.

- Longer stripes (i.e. 1x40degrees) of moving dots induce significantly more compelling vection than shorter stripes (i.e. 1x5degrees).
- Two narrow stripes of moving dots placed at different peripheral horizontal locations (i.e. 30, 45, and 70 degrees deviated from the center of straight gaze of each eye) induce similar levels of vection.
- A theory, the Connection Theory, was proposed and tested. The Connection Theory predicts that viewers "connect" the two narrow/small stimuli (i.e. 1x5 degrees) at each side of the peripheral vision and perceive them as a part of the outer-environment, and he/she is looking through two small windows.
- After reporting circular vection while keeping both eyes open to watch the two stripes of moving dots placed at the peripheral vision, closing one eye (i.e. seeing only one stimulus) does not stop circular vection immediately. This is consistent with the predictions of the Connection Theory.
- Two long stripes (1x40 degrees) of dots moving in the opposite directions located at the peripheral vision induces significantly more compelling vection than two short stripes (1x5 degrees) of moving dots placed at the same locations. However, when the two stripes were placed closer towards the central vision, the increase in vection induced by the longer stripes over the shorter stripes disappears. This may be explained by the predictions that the viewers have higher difficulty to connect the two long stripes as part of a rotating pattern when the two stripes are too close to each other. (See the Connection Theory.)
- Watching moving dots in small FOVs (i.e. two stripes of 1x5 degrees) placed at the central vision can induce vection as well.

8.2. Conclusions

Detailed results and discussions of Experiment 1&2, 3, 4, 5, and 6 are included in Chapter 3, 4, 5, 6 and 7 respectively. In this section, overall outlook of the vection perception at narrow/small FOVs is illustrated through percentage of subjects who reported vection at each of the conditions tested in all of the experiments (Tables 8.1 to 8.5).

	Ceiling Light OFF				Ceiling Light ON			
	WITHOUT Cardboard		WITH Cardboard		WITHOUT Cardboard		WITH Cardboard	
	to Down	to Up	to Down	to Up	to Down	to Up	to Down	to Up
Speed_1	87.5	93.75	93.75	93.75	50	43.75	56.25	50
Speed_2	87.5	93.75	100	100	43.75	43.75	50	68.75
Speed_3	93.75	93.75	100	100	43.75	31.25	62.5	56.25
Speed_4	100	100	100	100	37.5	50	75	68.75

Table 8.1: Percentage of subjects who reported vection at each condition of Experiment 1 (sample size 16)

	Ceiling Light OFF				Ceiling Light ON			
	WITHOUT Cardboard		WITH Cardboard		WITHOUT Cardboard		WITH Cardboard	
	to Down	to Up	to Down	to Up	to Down	to Up	to Down	to Up
Speed_1	92.31	92.31	100	100	38.46	61.54	84.62	84.62
Speed_4	100	92.31	100	100	76.92	61.54	100	92.31

Table 8.2: Percentage of subjects who reported vection at each condition of Experiment 2 (sample size 13)

		Direction Of Stimuli			
		Linear Stimuli		Circular Stimuli*	
		DD	UU	DU	UD**
Vertical FOV	5 degree	68.75	81.25	56.25	56.25
	10 degree	93.75	93.75	68.75	50
	20 degree	93.75	100	87.5	81.25
	40 degree	100	100	100	87.5

Table 8.3: Percentage of subjects who reported vection at each condition of Experiment 3 (sample size 16) (*Circular Stimuli consisted of two linear stripes going in opposite direction. It was named circular because majority of subjects reported circular vection to such stimuli.) (**Initial letter of direction (i.e. U or D) of left stripe is shown on the left, and that of right stripe is show on the right. For example, UD refers to stimuli where left stripe goes upward and right stripe goes downward.)

		Stimuli Direction			
		Linear Stimuli		Circular Stimuli*	
		DD	UU	DU	UD**
Horizontal Location = 30deg	Vertical FOV=5deg	75.00	68.75	43.75	50.00
	Vertical FOV=40deg	81.25	87.50	75.00	75.00
Horizontal Location = 45deg	Vertical FOV=5deg	68.75	68.75	56.25	37.50
	Vertical FOV=40deg	87.50	75.00	87.50	87.50
Horizontal Location = 70deg	Vertical FOV=5deg	56.25	68.75	50.00	43.75
	Vertical FOV=40deg	87.50	87.50	87.50	93.75

Table 8.4: Percentage of subjects who reported vection at each condition of Experiment 4 (sample size 16) (*Circular Stimuli consisted of two linear stripes going in opposite direction. It was named circular because majority of subjects reported circular vection to such stimuli.) (**Initial letter of direction (i.e. U or D) of left stripe is shown on the left, and that of right stripe is show on the right. For example, UD refers to stimuli where left stripe goes upward and right stripe goes downward.)

Vertical FOV	Percentage of subjects who reported vection
5 degree	41.18
10 degree	35.29
40 degree	52.94

Table 8.5: Percentage of subjects who reported vection at each condition of Experiment 6 at central vision (sample size 17)

Percentages of subjects who reported vection at each condition of each experiment are presented in Table 8.1 - 8.5. Analysis of percentages of subjects who reported vection for certain conditions consolidates the findings of statistical tests and provides more insights. A few of these insights are denoted below:

- In Experiment 1, 100% of the subjects reported vection when the ceiling light was off and the speed was highest (i.e. Speed_4). For the medium speed levels (i.e. Speed_2 and Speed_3), addition to keeping ceiling light off, frontal occultation (i.e. holding a cardboard) is needed for inducing vection among all of the subjects of Experiment 1. (See Table 8.1)
- In Experiment 1, the percentage of subjects who reported vection when ceiling light was off ranges between 87.5% and 100% (for each combination of frontal occultation condition, stimuli direction, and speed level). However, when the ceiling light was on the percentage ranges between 31.25% and 75%. It means that the lowest percentage under ceiling light off (i.e. 87.5%) is still bigger than the highest percentage under ceiling light on (i.e. 75%). Same claim is true for Experiment 2 as well (See Table 8.2). For this reason, the Experiments 3-6 were conducted with ceiling light off condition.
- In Experiment 3, percentage of subjects who reported vection for linear stimuli is higher than that for circular stimuli in each condition. (See Table 8.3)

- Although there are some cells in Tables 8.1-8.3 having the number 100%, there is no such cell in Table 8.4 because two of the subjects who were newly recruited to the experiment haven't reported vection for almost all of the conditions.

8.3. Limitations and Suggestions for Future Work

Although findings of this thesis enlighten our understanding of vection induced by moving dots of narrow/small FOVs, there are a few limitations. For example, participants of all experiments were young adults (ages ranging between 18 and 31). Children and elderly may have slightly different vection perception responses.

In this study, stimuli consisted of vertical stripes only. Therefore, the results represent the facts of vertical stripes. In a future work, it is recommended to test horizontal stripes as well.

Moreover, only random dot pattern was tested in this experiment. Future works to extend the scope to other moving stimuli such as virtual environments are desirable.

REFERENCES

Allison, R. S., Howard, I. P., & Zacher, J. E. (1999). Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room. *Perception, 28*, 299-306.

Bertenthal, B. I. (1993). Infants' perception of biomechanical motions: Intrinsic image and knowledge-based constraints. *Visual perception and cognition in infancy*, 175-214.

Bos, J. E., Bles, W., & Groen, E. L. (2008). A theory on visually induced motion sickness. *Displays, 29*(2), 47-57.

Bos, J. E., de Vries, S. C., van Emmerik, M. L., & Groen, E. L. (2010). The effect of internal and external fields of view on visually induced motion sickness. *Applied ergonomics, 41*(4), 516-521.

Bos, J. E., Ledegang, W. D., Lubeck, A. J., & Stins, J. F. (2013). Cinerama sickness and postural instability. *Ergonomics, 56*(9), 1430-1436.

Bos, J. E., Lubeck, A. J., & Stins, J. F. (2015). Framing vection: The effect of an Earth-fixed visual frame on optic roll-motion induced postural sway, subjective verticality, and motion sickness. *VIMS2015.* Tokyo.

Brandt, T., Bartenstein, P., Janek, A., & Dieterich, M. (1998). Reciprocal inhibitory visual-vestibular interaction. Visual motion stimulation deactivates the parieto-insular vestibular cortex. *Brain*, *121*, 1749-1758.

Brandt, T., Dichgans, J., & Koenig, E. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research, 16*(5), 476-491.

Dichgans, J., & Brandt, T. (1978). Visual-Vestibular Interaction: Effects on Self-Motion Perception and Postural Control. In R. Held, H. Leibowitz, & H. Teubner (Eds.), *Perception* (pp. 755-804). Springer.

Duh, H. B., Lin, J. J., Kenyon, R., Parker, D. E., & Furness, T. A. (2001). Effects of Field of View on Balance in an Immersive. *Proceedings of the IEEE Virtual Reality 2001*, (pp. 235-240). Yokohama, Japan.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Taylor & Francis.

Guo, C. T., Tsoi, C. W., Wong, Y. L., Yu, K. C., & So, R. H. (2013). Visually induced motion sickness during computer game playing. In P. T. McCabe (Ed.), *Contemporary Ergonomics and Human Factors 2013: Proceedings of the international conference on Ergonomics & Human Factors 2013* (pp. 51-58). Cambridge, UK: Taylor & Francis.

Harvey, C., & Howarth, P. A. (2007). The Effect of Display Size on Visually-Induced Motion Sickness (VIMS) and Skin Temperature. *Proceedings of VIMS2007*, (pp. 96-103).

Hecht, S., Haig, C., & Chase, A. M. (1937). The Influence of Light Adaptation on Subsequent Dark Adaptation of the Eye. *The Journal of General Physiology*, 831-852.

Hettinger, L. J., Berbaum, K. S., Kennedy, R. S., Dunlap, W. P., & Nolan, M. D. (1990). Vection and simulator sickness. *Military Psychology, 2*(3), 171-181.

Howard, I. P. (2012). *Perceiving in depth, volume 1: basic mechanisms.* Oxford University Press.

Ji, T.T., So, R.H.Y., & Cheung, R.T.F. (2009). Isolating the Effects of Vection and Optokinetic Nystagmus on Optokinetic Rotation-Induced Motion Sickness. *Human Factors, 51*(5), 739-751.

Johansson, G. (1977). Studies on visual perception of locomotion. *Perception, 6*, 365-376.

Johansson, G., Hoftsen, C. V., & Jansson, G. (1980). Event Perception. *Annual Review of Psychology*, 27-63.

Kennedy, R. S., Drexler, J., & Kennedy, R. C. (2010). Research in visually induced motion sickness. *Applied Ergonomics*(41), 494-503.

Kenyon, R. V., & Kneller, E. W. (1993). The Effects of Field of View Size on the Control of Roll Motion. *IEEE Transactions on Systems, Man, and Cybernetics*, (pp. 183-193).

Keshavarz, B., Riecke, B. E., Hettinger, L. J., & Campos, J. L. (2015). Vection and visually induced motion sickness: how are they related? *Frontiers in Psychology, 6*.

Khalid, H., Turan, O., & Bos, J. E. (2011). Theory of a subjective vertical–horizontal conflict physiological motion sickness model for contemporary ships. *Journal of marine science and technology*, *16*(2), 214-225.

Knapp, J. M., & Loomis, J. M. (2004). Limited Field of View of Head-Mounted Displays Is Not the Cause of Distance Underestimation in Virtual Environments. *Presence, 13*(5), 572-577.

Knight, B., & Johnston, A. (1997). The role of movement in face recognition. *Visual cognition*, *4*(3), 265-273.

Lee, D. N., Young, D. S., & Rewt, D. (1992). How do somersaulters land on their feet? *Journal of Experimental Psychology: Human Perception and Performance*, 1195.

Leibowitz, H. W., Shupert, C. L., & Post, R. B. (1983). The two modes of visual processing: Implications for spatial orientation. *Peripheral vision horizon display (PVHD)* (pp. 41-44). NASA conference publication.

Lin, J. J., Duh, H. B., Parker, D. E., Abi-Rached, H., & Furness, T. A. (2002). Effects of Field of View on Presence, Enjoyment, Memory, and Simulator Sickness in a Virtual Environment. *Proceedings of the IEEE Virtual Reality 2002*, (pp. 164-171). Orlando, USA.

Lo, W.T., & So, R.H.Y. (2001). Cybersickness in the presence of scene rotational movements along different axes. *Applied Ergonomics, 32*(1), 1-14.

Mestre, D. (1992). Visual Perception of Self-motion. In P. a. Elliot, *Vision and Motor Control* (pp. 421-438). Elsevier Science Publishers.

Owen, D. H. (1990). Lexicon of terms for the perception and control of self-motion and orientation. In R. Warren, & A. H. Wertheim, *Perception and Control of Self-Motion* (pp. 33-50). Lawrence Erlbaum Associates Publishers.

Palmisano, S., Allison, R. S., Schira, M. M., & Barry, R. J. (2015). Future challenges for vection research: definitions, functional significance, measures, and neural bases. *Frontiers in Psychology, 6*.

Ramachandran, V. S. (1992). Blind spots. *Scientific American*, *266*(5), 86-91.

Riecke, B. E. (2009). Cognitive and higher-level contributions to illusory self-motion perception ("vection") - Does the possibility of actual motion affect vection?-. *The Japanese Journal of Psychonomic Science, 28*(1), 135-139.

Riecke, B. E. (2010). *Compelling Self-Motion Through Virtual Environments without Actual Self-Motion - Using Self-Motion Illusions ("Vection") to Improve User Experience in VR.* INTECH Open Access Publisher.

Rocchesso, D., & Fontana, F. (2003). *The sounding object.*

So, R.H.Y., & Ujike, H. (2010). Visually induced motion sickness, visual stress and photosensitive epileptic seizures: What do they have in common? – Preface to the special issue. *Applied Ergonomics, 41*, 491-493.

So, R.H.Y., Finney, C. M., & Goonetilleke, R. S. (1999). Motion sickness susceptibility and occurrence in Hong Kong Chinese. In *Contemporary Ergonomics 1999.* Taylor & Francis.

So, R.H.Y., Lo, W.T., & Ho, A.T. (2001). Effects of navigation speed on motion sickness caused by an immersive virtual environment. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 43*(3), 452-461.

Spector, R. H. (1990). Visual Fields. In H. Walker, W. Hall, & J. Hurst, *Clinical Methods: The History, Physical, and Laboratory Examinations* (pp. 565-572). Boston: Butterworth Publishers.

Spillmann, L., Otte, T., Hamburger, K., & Magnussen, S. (2006). Perceptual filling-in from the edge of the blind spot. *Vision research, 46*(25), 4252-4257.

Stern, R. M., Hu, S., Anderson, R. B., Leibowitz, H. W., & Koch, K. L. (1990). The effects of fixation and restricted visual field on vection-induced motion sickness. *Aviation, Space, and Environmental Medicine*, *61*(8), 712-715.

Trutoiu, L. C., Mohler, B. J., Schulte-Pelkum, J., & H., B. H. (2009). Circular, linear, and curvilinear vection in a large-screen virtual environment. *Computer & Graphics*, *33*, 47-58.

van Emmerik, M. L., de Vries, S. C., & Bos, J. E. (2011). Internal and external fields of view affect cybersickness. *Displays, 32*(4), 169-174.

Warren, R. (1990). Preliminary questions for the study of egomotion. In R. Warren, & A. H. Wertheim, *Perception and Control of Self-Motion* (pp. 3-32). Lawrence Erlbaum Associates Publishers.

Warren, W. H. (1995). Self-Motion: Visual Perception and Visual Control. In W. E. Rogers, *Perception of Space and Motion* (pp. 263-325). Academic Press Inc.

Warren, W. H., & Kurtz, K. J. (1992). The role of central and peripheral vision in perceiving the direction of self-motion. *Perception & Psychophysics, 51*(5), 443-454.

Wolpert, L. (1990). Field-of-view information for self-motion perception. In R. Warren, & A. Wertheim, *Perception & Control of Self-Motion* (pp. 101-126). Lawrence Erlbaum Associates Publishers.

Zur, D., & Ullman, S. (2003). Filling-in of retinal scotomas. *Vision research, 43*(9), 971-982.

APPENDICES

APPENDIX 1: Data of Experiment 1

Subject A

ConditionNumber	CeilingLight	FrontalOccultation	StimuliDirection	Speed	OnsetTimeA	RatingA
1	OFF	w/o Cardboard	Down	Speed_1	5	4
2	OFF	w/o Cardboard	Down	Speed_2	6	6
3	OFF	w/o Cardboard	Down	Speed_3	12	4
4	OFF	w/o Cardboard	Down	Speed_4	4	4
5	OFF	w/o Cardboard	Up	Speed_1	4	4
6	OFF	w/o Cardboard	Up	Speed_2	2	4
7	OFF	w/o Cardboard	Up	Speed_3	2	4
8	OFF	w/o Cardboard	Up	Speed_4	9	6
9	OFF	with Cardboard	Down	Speed_1	6	4
10	OFF	with Cardboard	Down	Speed_2	8	6
11	OFF	with Cardboard	Down	Speed_3	10	6
12	OFF	with Cardboard	Down	Speed_4	10	4
13	OFF	with Cardboard	Up	Speed_1	3	4
14	OFF	with Cardboard	Up	Speed_2	11	4
15	OFF	with Cardboard	Up	Speed_3	3	6
16	OFF	with Cardboard	Up	Speed_4	5	4
17	ON	w/o Cardboard	Down	Speed_1	19	1
18	ON	w/o Cardboard	Down	Speed_2	22	1
19	ON	w/o Cardboard	Down	Speed_3	121	0
20	ON	w/o Cardboard	Down	Speed_4	121	0
21	ON	w/o Cardboard	Up	Speed_1	23	2
22	ON	w/o Cardboard	Up	Speed_2	11	2
23	ON	w/o Cardboard	Up	Speed_3	121	0
24	ON	w/o Cardboard	Up	Speed_4	31	2
25	ON	with Cardboard	Down	Speed_1	15	6
26	ON	with Cardboard	Down	Speed_2	16	4
27	ON	with Cardboard	Down	Speed_3	12	4
28	ON	with Cardboard	Down	Speed_4	22	2
29	ON	with Cardboard	Up	Speed_1	15	4
30	ON	with Cardboard	Up	Speed_2	12	2
31	ON	with Cardboard	Up	Speed_3	13	4
32	ON	with Cardboard	Up	Speed_4	27	4

	Subject B		Subject C		Subject D	
ConditionNumber	OnsetTimeB	RatingB	OnsetTimeC	RatingC	OnsetTimeD	RatingD
1	6	5	7	6	121	0
2	2	6	16	5	121	0
3	4	4	7	6	65	1
4	5	6	7	6	12	1
5	10	5	4	5	121	0
6	5	5	7	5	121	0
7	2	5	7	6	121	0
8	2	4	6	6	24	1
9	6	6	38	4	121	0
10	1	6	11	5	30	1
11	1	6	8	5	16	1
12	1	6	7	5	16	1
13	5	5	11	4	121	0
14	5	6	6	5	37	1
15	1	6	4	6	7	2
16	2	5	11	6	10	2
17	34	1	121	0	121	0
18	108	1	121	0	121	0
19	121	0	20	1	121	0
20	78	1	121	0	121	0
21	34	1	30	1	121	0
22	39	3	121	0	121	0
23	37	1	121	0	121	0
24	17	2	121	0	121	0
25	30	4	22	1	121	0
26	93	4	121	0	121	0
27	18	4	18	1	121	0
28	26	1	27	1	121	0
29	15	3	16	1	121	0
30	26	4	15	2	121	0
31	10	4	121	0	121	0
32	40	1	14	1	121	0

	Subject E		Subject F		Subject G	
ConditionNumber	OnsetTimeE	RatingE	OnsetTimeG	RatingG	OnsetTimeH	RatingH
1	18	5	6	1	53	4
2	10	4	4	2	24	3
3	7	4	4	3	32	5
4	9	5	4	2	47	5
5	14	4	5	3	45	2
6	11	4	10	2	103	2
7	9	4	4	2	18	5
8	12	5	3	3	9	4
9	9	5	7	2	63	2
10	20	3	6	2	20	3
11	11	4	7	2	13	4
12	6	5	5	3	19	3
13	16	4	9	1	68	2
14	12	4	5	2	38	2
15	8	4	7	3	9	4
16	15	4	6	3	45	5
17	121	0	121	0	47	2
18	121	0	121	0	121	0
19	121	0	121	0	20	1
20	121	0	121	0	121	0
21	121	0	121	0	121	0
22	121	0	121	0	95	1
23	121	0	121	0	121	0
24	121	0	121	0	109	1
25	32	1	121	0	121	0
26	16	2	121	0	24	1
27	28	2	121	0	47	1
28	34	2	121	0	46	2
29	20	1	121	0	121	0
30	66	1	121	0	121	0
31	72	1	121	0	121	0
32	59	1	121	0	92	1

	Subject H		Subject I		Subject J	
ConditionNumber	OnsetTimeI	RatingI	OnsetTimeJ	RatingJ	OnsetTimeK	RatingK
1	5	3	89	1	30	2
2	5	3	23	3	32	3
3	5	4	23	3	30	2
4	4	4	22	3	26	5
5	7	2	35	2	14	6
6	5	4	28	2	20	3
7	4	4	19	2	10	5
8	2	4	8	4	17	6
9	4	3	42	3	19	2
10	3	4	24	3	14	4
11	3	4	18	4	12	3
12	2	4	7	5	14	4
13	6	3	31	2	29	5
14	4	3	11	3	15	4
15	4	4	12	3	13	3
16	3	4	18	5	11	3
17	6	2	34	1	121	0
18	4	2	65	1	121	0
19	6	2	13	2	121	0
20	4	3	121	0	121	0
21	6	2	121	0	121	0
22	4	3	121	0	121	0
23	5	2	21	2	121	0
24	4	2	38	1	121	0
25	5	2	14	2	48	1
26	4	2	7	2	121	0
27	7	3	13	3	121	0
28	5	3	35	1	121	0
29	6	2	73	1	121	0
30	5	2	13	2	21	1
31	4	3	17	2	121	0
32	4	2	19	3	121	0

	Subject K		Subject L		Subject M	
ConditionNumber	OnsetTimeL	RatingL	OnsetTimeM	RatingM	OnsetTimeN	RatingN
1	9	4	3	2	35	4
2	4	6	6	4	37	3
3	3	5	3	5	12	5
4	6	6	3	6	40	5
5	8	4	11	4	35	5
6	3	6	6	3	15	2
7	3	6	3	6	15	4
8	3	6	4	5	13	3
9	7	6	12	2	59	5
10	4	4	4	3	48	6
11	3	4	3	5	22	5
12	5	6	5	6	13	5
13	5	6	7	3	41	4
14	13	2	4	3	21	6
15	9	6	2	5	19	2
16	4	6	4	6	23	4
17	7	4	121	0	121	0
18	5	2	121	0	110	1
19	17	2	121	0	121	0
20	9	2	24	1	121	0
21	68	2	121	0	68	1
22	98	2	121	0	121	0
23	80	2	121	0	121	0
24	9	2	121	0	9	2
25	121	0	121	0	121	0
26	15	2	121	0	121	0
27	37	1	121	0	121	0
28	12	4	20	1	8	1
29	16	2	121	0	49	1
30	27	2	121	0	31	1
31	45	2	121	0	24	1
32	6	2	30	1	121	0

	Subject N		Subject O		Subject P	
ConditionNumber	OnsetTimeO	RatingO	OnsetTimeP	RatingP	OnsetTimeQ	RatingQ
1	121	0	11	4	19	2
2	34	4	14	1	121	0
3	121	0	12	2	28	4
4	40	2	11	3	42	1
5	26	2	15	1	33	2
6	31	3	12	1	34	3
7	16	3	27	1	34	2
8	22	4	5	4	31	2
9	26	1	7	3	30	6
10	29	5	4	4	33	5
11	19	3	9	3	23	4
12	45	5	9	5	26	3
13	33	4	16	4	37	1
14	24	2	24	1	31	5
15	47	3	10	3	39	3
16	16	4	7	3	58	2
17	43	1	11	4	121	0
18	121	0	21	2	121	0
19	27	1	6	2	121	0
20	19	1	10	4	121	0
21	121	0	23	2	121	0
22	19	1	11	1	121	0
23	121	0	14	3	121	0
24	121	0	28	3	121	0
25	40	2	18	3	121	0
26	121	0	88	1	121	0
27	65	1	5	3	121	0
28	38	2	6	4	121	0
29	121	0	121	0	121	0
30	21	2	18	2	121	0
31	28	1	10	1	121	0
32	53	1	17	2	121	0

APPENDIX 2: Data of Experiment 2

A Note: 7 out of 13 subjects of Experiment 2 have taken part in Experiment 1 too. Here are their corresponding subject numbers in Experiment 2 (number) and Experiment 1 (letter) listed in the table below.

Experiment 2	Experiment 1
Subject 1	Subject H
Subject 3	Subject L
Subject 4	Subject F
Subject 6	Subject B
Subject 8	Subject A
Subject 12	Subject G
Subject 13	Subject E

Subject 1

ConditionNumber	CeilingLight	FrontalOccultation	StimuliDirection	Speed	OnsetTime1	Rating1
1	OFF	w/o Cardboard	Down	Speed_1	8	2
2	OFF	w/o Cardboard	Down	Speed_4	18	3
3	OFF	w/o Cardboard	Up	Speed_1	29	2
4	OFF	w/o Cardboard	Up	Speed_4	20	3
5	OFF	with Cardboard	Down	Speed_1	13	3
6	OFF	with Cardboard	Down	Speed_4	20	4
7	OFF	with Cardboard	Up	Speed_1	26	2
8	OFF	with Cardboard	Up	Speed_4	6	5
9	ON	w/o Cardboard	Down	Speed_1	56	1
10	ON	w/o Cardboard	Down	Speed_4	55	3
11	ON	w/o Cardboard	Up	Speed_1	39	3
12	ON	w/o Cardboard	Up	Speed_4	51	2
13	ON	with Cardboard	Down	Speed_1	46	1
14	ON	with Cardboard	Down	Speed_4	24	3
15	ON	with Cardboard	Up	Speed_1	44	1
16	ON	with Cardboard	Up	Speed_4	15	3

	Subject 2		Subject 3		Subject 4	
ConditionNumber	OnsetTime2	Rating2	OnsetTime3	Rating3	OnsetTime4	Rating4
1	39	1	121	0	14	2
2	31	3	81	2	7	3
3	37	2	121	0	14	2
4	20	2	5	3	10	2
5	17	3	5	1	6	2
6	15	4	18	3	12	2
7	60	1	60	1	6	2
8	18	4	13	3	6	3
9	121	0	121	0	121	0
10	121	0	121	0	35	1
11	121	0	121	0	121	0
12	121	0	121	0	121	0
13	121	0	121	0	8	1
14	45	2	17	1	15	1
15	121	0	121	0	13	1
16	28	2	45	1	11	1

	Subject 5		Subject 6		Subject 7	
ConditionNumber	OnsetTime5	Rating5	OnsetTime6	Rating6	OnsetTime7	Rating7
1	10	2	4	4	2	4
2	5	3	6	4	7	1
3	7	2	3	4	7	4
4	21	2	4	4	121	0
5	3	2	4	3	2	4
6	4	5	2	4	2	3
7	7	3	4	5	10	3
8	3	4	3	4	9	1
9	121	0	121	0	30	2
10	54	1	58	1	22	1
11	121	0	46	2	121	0
12	121	0	23	2	121	0
13	6	2	11	3	8	3
14	6	3	4	3	16	1
15	15	2	4	1	10	2
16	20	2	5	2	121	0

	Subject 8		Subject 9		Subject 10	
ConditionNumber	OnsetTime8	Rating8	OnsetTime9	Rating9	OnsetTime10	Rating10
1	2	5	4	5	22	1
2	1	4	3	4	3	5
3	3	5	5	3	21	2
4	1	4	3	5	3	4
5	7	3	5	5	14	1
6	3	4	4	5	3	4
7	2	5	5	4	10	3
8	2	4	3	4	2	6
9	22	3	121	0	121	0
10	12	1	121	0	24	1
11	15	4	24	1	82	3
12	19	2	96	1	49	2
13	8	2	14	2	17	3
14	4	3	7	1	5	4
15	5	5	9	2	4	3
16	2	3	13	1	7	3

	Subject 11		Subject 12		Subject 13	
ConditionNumber	OnsetTime11	Rating11	OnsetTime12	Rating12	OnsetTime13	Rating13
1	11	2	21	3	20	2
2	7	2	6	4	10	3
3	12	2	39	3	12	3
4	7	4	10	2	8	4
5	8	3	37	2	24	4
6	11	3	9	3	11	5
7	6	4	12	3	30	3
8	7	4	6	4	9	5
9	11	3	121	0	7	2
10	8	3	16	2	7	3
11	7	4	64	1	48	1
12	5	4	27	2	6	3
13	11	4	23	2	19	3
14	12	3	16	3	8	3
15	8	2	25	2	16	2
16	5	3	7	3	5	4

APPENDIX 3: Data of Experiment 3

				Subject 1	
ConditionNo	VectionType	StimuliDirection	VerticalFOV	OnsetTime1	Rating1
1	Linear	DD	5	10	2
2	Linear	DD	10	9	3
3	Linear	DD	20	9	3
4	Linear	DD	40	7	3
5	Linear	UU	5	4	3
6	Linear	UU	10	14	3
7	Linear	UU	20	12	3
8	Linear	UU	40	3	4
9	Circular	AC	5	10	3
10	Circular	AC	10	12	2
11	Circular	AC	20	14	2
12	Circular	AC	40	10	3
13	Circular	C	5	13	3
14	Circular	C	10	15	2
15	Circular	C	20	14	2
16	Circular	C	40	8	3

	Subject 2		Subject 3		Subject 4	
ConditionNo	OnsetTime2	Rating2	OnsetTime3	Rating3	OnsetTime4	Rating4
1	121	0	27	2	121	0
2	15	2	48	1	121	0
3	4	3	20	3	121	0
4	8	3	24	3	26	1
5	119	2	26	3	121	0
6	15	2	24	4	121	0
7	9	3	19	4	19	2
8	5	2	16	4	10	3
9	121	0	40	1	121	0
10	121	0	31	3	121	0
11	45	1	19	2	56	2
12	29	2	17	5	40	5
13	45	1	21	2	121	0
14	26	1	27	3	121	0
15	74	2	31	4	29	4
16	121	0	48	3	20	4

	Subject 5		Subject 6		Subject 7	
ConditionNo	OnsetTime5	Rating5	OnsetTime6	Rating6	OnsetTime7	Rating7
1	1	1	121	0	5	1
2	1	2	7	2	7	2
3	1	2	10	3	13	3
4	1	2	5	3	3	3
5	1	1	121	0	4	2
6	1	2	10	1	9	2
7	1	3	7	2	3	3
8	1	3	5	3	5	4
9	23	1	121	0	4	1
10	10	1	9	1	5	1
11	5	1	7	1	3	2
12	1	1	8	2	5	3
13	27	1	121	0	15	1
14	1	1	6	1	5	2
15	15	1	6	2	3	3
16	9	1	8	2	5	3

	Subject 8		Subject 9		Subject 10	
ConditionNo	OnsetTime8	Rating8	OnsetTime9	Rating9	OnsetTime10	Rating10
1	14	2	121	0	121	0
2	33	2	9	3	2	3
3	21	3	4	4	2	3
4	20	3	3	3	3	4
5	11	2	16	2	7	4
6	27	4	12	3	2	3
7	13	3	14	4	3	3
8	8	4	11	5	5	3
9	121	0	121	0	22	3
10	121	0	121	0	20	1
11	35	2	7	2	58	1
12	12	2	10	3	18	1
13	25	2	121	0	22	3
14	121	0	121	0	121	0
15	48	2	19	2	10	2
16	4	3	22	2	6	1

	Subject 11		Subject 12		Subject 13	
ConditionNo	OnsetTime11	Rating11	OnsetTime12	Rating12	OnsetTime13	Rating13
1	13	1	6	3	5	4
2	5	2	8	2	7	4
3	5	2	11	3	3	5
4	2	3	18	3	4	5
5	121	0	12	2	6	2
6	30	1	10	1	4	5
7	11	1	16	2	2	5
8	7	2	6	2	5	5
9	13	1	121	0	4	3
10	13	1	121	0	1	3
11	121	0	121	0	2	3
12	8	2	20	2	9	2
13	121	0	121	0	4	3
14	121	0	121	0	5	3
15	121	0	8	1	2	3
16	8	2	121	0	1	3

	Subject 14		Subject 15		Subject 16	
ConditionNo	OnsetTime14	Rating14	OnsetTime15	Rating15	OnsetTime16	Rating16
1	46	6	3	2	67	1
2	25	2	2	3	4	3
3	29	6	4	3	2	4
4	48	6	1	3	2	4
5	21	3	23	1	4	4
6	26	2	3	3	2	4
7	60	3	16	1	3	3
8	42	5	5	2	2	4
9	121	0	16	1	17	2
10	79	1	10	2	28	1
11	115	1	7	2	17	2
12	44	6	4	2	6	3
13	121	0	121	0	25	1
14	121	0	121	0	92	1
15	121	0	121	0	5	1
16	80	1	110	1	14	3

APPENDIX 4: Data of Experiment 4

					Subject 1	
ConditionNo	HorizontalLocation	VerticalFOV	VectionType	StimuliDirection	OnsetTime1	Rating1
1	30	5	Linear	DD	11	3
2	30	5	Linear	UU	8	5
3	30	5	Circular	AC	9	1
4	30	5	Circular	C	49	4
5	30	40	Linear	DD	10	4
6	30	40	Linear	UU	12	3
7	30	40	Circular	AC	4	3
8	30	40	Circular	C	3	3
9	45	5	Linear	DD	36	3
10	45	5	Linear	UU	5	2
11	45	5	Circular	AC	5	3
12	45	5	Circular	C	14	2
13	45	40	Linear	DD	8	2
14	45	40	Linear	UU	6	1
15	45	40	Circular	AC	6	2
16	45	40	Circular	C	1	2
17	70	5	Linear	DD	11	4
18	70	5	Linear	UU	20	2
19	70	5	Circular	AC	6	4
20	70	5	Circular	C	3	2
21	70	40	Linear	DD	4	1
22	70	40	Linear	UU	3	3
23	70	40	Circular	AC	3	2
24	70	40	Circular	C	6	3

	Subject 2		Subject 3		Subject 4	
ConditionNo	OnsetTime2	Rating2	OnsetTime3	Rating3	OnsetTime4	Rating4
1	121	0	17	1	121	0
2	121	0	8	2	121	0
3	121	0	121	0	121	0
4	121	0	121	0	121	0
5	15	1	4	3	121	0
6	24	1	4	4	13	3
7	19	1	19	1	14	3
8	34	1	121	0	121	0
9	121	0	7	1	121	0
10	121	0	15	1	121	0
11	121	0	121	0	121	0
12	121	0	121	0	121	0
13	7	1	1	3	39	6
14	121	0	2	5	121	0
15	14	1	7	1	7	3
16	6	1	4	1	10	2
17	121	0	4	2	121	0
18	121	0	13	1	121	0
19	121	0	121	0	121	0
20	121	0	121	0	121	0
21	13	2	3	3	11	3
22	21	2	2	4	13	2
23	12	1	10	2	7	3
24	19	1	16	2	6	3

	Subject 5		Subject 6		Subject 7	
ConditionNo	OnsetTime5	Rating5	OnsetTime6	Rating6	OnsetTime7	Rating7
1	15	1	4	5	121	0
2	8	2	3	1	121	0
3	68	1	2	2	121	0
4	16	1	2	1	121	0
5	2	4	2	4	121	0
6	2	2	4	2	121	0
7	3	3	1	2	121	0
8	2	4	1	2	121	0
9	11	1	3	1	121	0
10	7	3	3	1	121	0
11	36	1	2	1	121	0
12	18	1	3	1	121	0
13	2	3	4	2	121	0
14	6	3	5	1	121	0
15	6	4	3	3	121	0
16	3	3	2	2	121	0
17	11	3	7	4	121	0
18	20	2	11	1	121	0
19	6	2	13	2	121	0
20	4	2	32	1	121	0
21	5	4	4	2	121	0
22	5	4	14	3	121	0
23	7	4	9	1	121	0
24	9	4	5	3	121	0

	Subject 8		Subject 9		Subject 10	
ConditionNo	OnsetTime8	Rating8	OnsetTime9	Rating9	OnsetTime10	Rating10
1	4	1	16	1	3	2
2	4	1	9	2	6	1
3	6	1	121	0	2	1
4	11	1	121	0	2	2
5	1	3	9	3	1	4
6	4	2	3	3	5	5
7	4	1	23	1	1	4
8	2	2	21	1	4	1
9	4	1	7	1	3	2
10	2	1	38	1	2	2
11	5	1	121	0	1	1
12	4	1	121	0	1	1
13	1	3	1	3	1	4
14	2	2	4	3	1	4
15	3	2	114	1	1	1
16	2	3	106	1	1	3
17	2	1	25	1	1	2
18	3	1	3	2	5	2
19	46	1	121	0	1	2
20	2	1	121	0	1	1
21	2	4	6	3	1	5
22	1	3	3	3	1	2
23	2	2	32	2	7	2
24	1	3	5	2	3	2

	Subject 11		Subject 12		Subject 13	
ConditionNo	OnsetTime11	Rating11	OnsetTime12	Rating12	OnsetTime13	Rating13
1	121	0	32	3	31	4
2	121	0	27	1	28	5
3	121	0	121	0	121	0
4	121	0	121	0	106	1
5	121	0	14	3	26	3
6	121	0	30	3	11	3
7	121	0	13	4	121	0
8	121	0	29	3	74	1
9	121	0	121	0	27	4
10	121	0	19	4	48	4
11	121	0	121	0	119	1
12	121	0	121	0	121	0
13	121	0	21	4	30	3
14	121	0	13	2	30	3
15	121	0	91	2	36	3
16	121	0	8	3	52	2
17	121	0	21	2	121	0
18	121	0	17	2	21	4
19	121	0	121	0	37	2
20	121	0	121	0	89	3
21	121	0	32	3	8	3
22	121	0	15	3	47	3
23	121	0	14	3	58	3
24	30	6	21	3	70	3

	Subject 14		Subject 15		Subject 16	
ConditionNo	OnsetTime14	Rating14	OnsetTime15	Rating15	OnsetTime16	Rating16
1	32	2	14	2	9	3
2	121	0	19	2	8	2
3	24	2	121	0	17	2
4	121	0	30	1	7	1
5	5	3	9	3	4	4
6	14	4	6	4	6	3
7	121	0	12	2	11	3
8	98	3	16	2	5	3
9	1	3	13	2	11	2
10	121	0	4	2	10	2
11	51	2	4	2	17	2
12	121	0	121	0	11	2
13	2	3	12	3	5	3
14	11	3	7	3	4	4
15	50	1	5	2	6	3
16	82	2	6	2	8	3
17	121	0	121	0	9	2
18	121	0	8	2	14	3
19	121	0	43	1	13	3
20	121	0	121	0	15	2
21	2	4	8	4	19	2
22	16	3	3	3	5	3
23	28	3	27	2	5	3
24	38	2	9	2	14	2

APPENDIX 5: Data of Experiment 5

					Subject 1	
ConditionNo	HowManyEyes AreOpen	WhichEyeIsOpen	StimuliType	StimuliDirection	OnsetTime1	Rating1
1.A	Both	Both	Linear	D	11	3
1.B	OnlyOne	Right	Linear	D	30	3
2.A	Both	Both	Linear	U	7	3
2.B	OnlyOne	Right	Linear	U	30	2
3.A	Both	Both	Circular	DU	29	2
3.B	OnlyOne	Right	Circular	DU	8.768	3
4.A	Both	Both	Circular	UD	31	2
4.B	OnlyOne	Right	Circular	UD	8.704	2
5.A	Both	Both	Linear	D	7	3
5.B	OnlyOne	Left	Linear	D	30	2
6.A	Both	Both	Linear	U	5	3
6.B	OnlyOne	Left	Linear	U	30	2
7.A	Both	Both	Circular	DU	11	2
7.B	OnlyOne	Left	Circular	DU	15.21	3
8.A	Both	Both	Circular	UD	2.5	3
8.B	OnlyOne	Left	Circular	UD	15.351	2

	Subject 2		Subject 3		Subject 4	
ConditionNo	OnsetTime2	Rating2	OnsetTime3	Rating3	OnsetTime4	Rating4
1.A	59	2	6	3	15	3
1.B	7.144	0	30	3	3.008	0
2.A	X120	X	2	3	48	3
2.B	X	X	30	3	25.599	0
3.A	44	3	5	2	33	2
3.B	4.103	0	0.832	1	1.487	0
4.A	27	3	1	3	22	1
4.B	2.09	0	1.855	3	3.968	0
5.A	19	2	2	3	23	3
5.B	11.357	0	30	3	26.22	0
6.A	16	2	1	3	33	3
6.B	6.013	1	30	3	1.664	3
7.A	101	2	2	2	76	1
7.B	3.916	0	1.52	3	1.152	3
8.A	60	3	2	2	41	1
8.B	4.851	1	1.744	3	4.383	3

	Subject 5		Subject 6		Subject 7	
ConditionNo	OnsetTime5	Rating5	OnsetTime6	Rating6	OnsetTime7	Rating7
1.A	18	3	66	3	4	2
1.B	30	4	30	3	30	2
2.A	10	4	X120	X	7	3
2.B	30	3	X	X	30	3
3.A	103	3	99	2	31	1
3.B	7.504	4	10.927	3	12.44	2
4.A	118	3	38	3	12	2
4.B	4.976	4	10.463	2	11.344	3
5.A	35	4	106	2	8	2
5.B	30	4	12.88	0	30	2
6.A	64	4	X120	X	12	2
6.B	30	4	X	X	30	3
7.A	110	3	59	3	11	2
7.B	30	4	30	3	11.856	3
8.A	67	3	74	3	8	2
8.B	30	4	12.928	4	11.536	3

	Subject 8		Subject 9		Subject 10	
ConditionNo	OnsetTime8	Rating8	OnsetTime9	Rating9	OnsetTime10	Rating10
1.A	9	1	4	1	45	2
1.B	30	1	5.023	0	1.327	0
2.A	24	1	25	1	10	2
2.B	30	1	3.169	0	4.896	0
3.A	7	1	10	1	4	2
3.B	1.616	0	2.383	0	4.383	0
4.A	7	2	6	1	34	2
4.B	0.543	0	4.127	0	1.055	0
5.A	12	1	4	1	10	2
5.B	30	1	10.735	0	2.943	0
6.A	23	1	26	1	2	4
6.B	30	1	2.319	0	12.606	0
7.A	9	1	14	2	5	3
7.B	0.499	0	3.151	0	1.487	0
8.A	4	2	35	1	4	3
8.B	0.5	0	2.417	0	0.959	0

	Subject 11		Subject 12		Subject 13	
ConditionNo	OnsetTime11	Rating11	OnsetTime12	Rating12	OnsetTime13	Rating13
1.A	28	3	8	4	24	2
1.B	30	3	30	4	30	4
2.A	24	3	16	4	33	3
2.B	30	3	30	3	30	5
3.A	7	2	9	3	31	4
3.B	30	2	0.543	4	6.863	0
4.A	15	3	13	3	28	4
4.B	30	2	1.152	4	12.544	4
5.A	39	2	4	3	31	3
5.B	1.839	0	30	3	30	5
6.A	79	1	10	4	24	6
6.B	12.016	0	30	4	30	6
7.A	29	3	10	3	39	4
7.B	30	3	0.927	4	13.85	5
8.A	20	2	14	3	36	2
8.B	5.856	0	2.623	4	8.031	0

	Subject 14		Subject 15		Subject 16	
ConditionNo	OnsetTime14	Rating14	OnsetTime15	Rating15	OnsetTime16	Rating16
1.A	5	3	14	4	21	1
1.B	30	2	30	3	30	2
2.A	21	3	27	4	36	2
2.B	30	3	30	3	30	2
3.A	1	3	20	2	13	2
3.B	6.943	2	4.976	4	4.991	0
4.A	7	3	17	3	X120	X
4.B	3.088	3	2.383	3	10.079	3
5.A	13	3	26	3	6	3
5.B	6.591	3	30	2	30	3
6.A	17	3	12	2	7	2
6.B	30	2	30	3	30	2
7.A	2	3	18	2	19	1
7.B	3.904	3	1.839	0	2.384	0
8.A	5	2	17	3	X120	X
8.B	7.551	3	5.935	3	X	X

APPENDIX 6: Data of Experiment 6

SubjectNo	VerticalFOV	OnsetTime	Rating
1	5	62	1
1	10	114	1
1	40	114	1
2	5	121	0
2	10	121	0
2	40	70	2
3	5	121	0
3	10	121	0
3	40	121	0
4	5	97	6
4	10	32	4
4	40	110	4
5	5	121	0
5	10	47	2
5	40	109	2
6	5	121	0
6	10	121	0
6	40	81	1
7	5	121	0
7	10	121	0
7	40	121	0
8	5	121	0
8	10	121	0
8	40	121	0
9	5	121	0
9	10	121	0
9	40	121	0
10	5	121	0
10	10	121	0
10	40	30	1

SubjectNo	VerticalFOV	OnsetTime	Rating
11	5	31	3
11	10	24	3
11	40	34	2
12	5	121	0
12	10	121	0
12	40	121	0
13	5	72	1
13	10	90	6
13	40	121	0
14	5	11	3
14	10	49	4
14	40	21	3
15	5	55	1
15	10	121	0
15	40	121	0
16	5	121	0
16	10	121	0
16	40	32	1
17	5	96	1
17	10	121	0
17	40	121	0