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The Effect of Motion Direction and Eccentricity on Vection, VR sickness and Head Movements in Virtual Reality

--Manuscript Draft--

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Abstract:	Virtual Reality experienced through head mounted displays often leads to vection, discomfort and sway in the user. This study investigated the effect of motion direction and eccentricity on these three phenomena using optic flow patterns displayed using the Valve Index. Visual motion stimuli were presented in the centre, periphery or far periphery and moved either in-depth (back and forth) or laterally (left and right). Overall vection was stronger for motion-in-depth compared to lateral motion. Additionally, eccentricity primarily affected stimuli moving in-depth with stronger vection for more peripherally presented motion patterns compared to more central ones. Motion direction affected the various aspects of VR sickness differently and modulated the effect of eccentricity on VR sickness . For stimuli moving in-depth far peripheral presentation caused more discomfort, whereas for lateral motion the central stimuli caused more discomfort. Stimuli moving in-depth led to more head movements in the anterior-posterior direction when the entire visual field was stimulated. Observers demonstrated more head movements in the anterior – posterior direction compared to the medio – lateral direction throughout the entire experiment independent of motion direction or eccentricity of the presented moving stimulus. A correlation showed a positive relationship between dizziness and vection duration and between general discomfort and sway. Identifying where in the visual field motion presented to an individual causes the least amount of VR sickness without losing vection and presence can guide development for Virtual Reality games, training and treatment programs.
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Cover Letter

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To
Michael Barnett-Cowan
Editor-in-Chief, Multisensory Research

4th March 2021

Dear Dr. Michael Barnett-Cowan,

We would like to resubmit our manuscript entitled: "The effect of motion direction and eccentricity on vection, VR sickness and head movements in Virtual Reality" as a research article to be published in Multisensory Research.
We think we have addressed all reviewers' comments in order to publish our manuscript in Multisensory Research.

We confirm that this manuscript has not been published elsewhere and is not under consideration by another journal.

Sincerely yours,

Adrian Park, Patrick Dickinson, Louise O'Hare, Julia Föcker, Katharina Pöhlmann

We would like to thank the reviewer and the editor for their helpful comments. We have addressed the following points. Thank you again for your time and assistance in improving the manuscript.

Reviewer 1:

Point 1: Now that the SSQ data have been added, the authors might want to explain the remarkable result that SSQ total scores were not significantly correlated with individual ratings of General Discomfort, Headache, Blurred Vision, Dizziness, or Eye Strain. All of those are even found within the SSQ as individual items, so one expects that they correlate with the SSQ total. On top of that, the SSQ scores are even slightly negatively correlated with all of the above. How could this be possible? This lack of reliability casts doubt on some of the measurements in the study, and the reader will require an explanation from the authors to abate these concerns.

Response 1:

The discomfort ratings not being related to the overall SSQ score was a surprising finding. We believe that it could be explained partly by the procedure of the experiment. Discomfort ratings were reported multiple times throughout the study while observers were immersed in the virtual environment and viewed the stimuli. Whereas the SSQ was filled out before and after the VR immersion. The discomfort ratings could possibly be measuring VR symptoms that are short-lived and only experienced while viewing the moving pattern and being immersed in the virtual environment and not afterwards. We have added a discussion of those findings to the manuscript, see page 36, line 11-22.

"Surprisingly, the overall SSQ scores and the individual discomfort ratings collected throughout the study showed no relationship with each other. The individual ratings were based on items within the SSQ scale and therefore a positive relationship between the scale and the ratings was expected. This difference might be partially explained by the timing of measurement. Individual discomfort ratings were collected multiple times throughout the study during which observers were immersed in the virtual environment, whilst the SSQ was filled out before and after the VR session. The discomfort ratings could be measuring a subjective experience of VR sickness symptoms that is short-lived and only experienced while immersed in VR and not afterwards. Similarly, MSSQ scores were not related with any of the other discomfort measures, suggesting that an individual's motion sickness susceptibility to experiences in the real world might not be suitable to predict or is even related to VR sickness experience in a virtual environment. "

Point 2: I notice that the authors collected the SSQ before and after the experiment. As far as I can see, the results of the first collection were not used or reported in the study. If so, could the authors clarify why were they collected?

Response 2: The SSQ results collected before the experiment were used as a baseline measure and subtracted from the SSQ results collected after the experiment. We have added an explanation of this to the measures section, see page 14 line 6-9.

"The SSQ was administered immediately prior to and immediately after the experimental condition. The pre-session scores served as a baseline measure and were subtracted from the scores collected after the experimental condition. The scores reported are the result of the subtraction."

Point 3: P36 L13: The sentence that starts with 'Suggesting' should be merged with the previous sentence, with a comma separating them.

Response 3: *Thank you for pointing this out to us. The manuscript has been adapted:*

*“*Again, this could be due to the motion signals particularly in the restricted conditions not being strong enough to elicit head movements related to the visual stimulus, suggesting that weaker motion signals can be used to elicit vection without causing sway in the user of HMDs.”

Title: The Effect of Motion Direction and Eccentricity on Vection, VR sickness and Head Movements in Virtual Reality

Running title: Vection and VR sickness in Virtual Reality

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Keywords: visual discomfort, VR sickness, virtual reality, vection, head movements, optic-flow

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Abstract

Virtual Reality experienced through head mounted displays often leads to vection, discomfort and sway in the user. This study investigated the effect of motion direction and eccentricity on these three phenomena using optic flow patterns displayed using the Valve Index. Visual motion stimuli were presented in the centre, periphery or far periphery and moved either in-depth (back and forth) or laterally (left and right). Overall vection was stronger for motion-in-depth compared to lateral motion. Additionally, eccentricity primarily affected stimuli moving in-depth with stronger vection for more peripherally presented motion patterns compared to more central ones. Motion direction affected the various aspects of VR sickness differently and modulated the effect of eccentricity on VR sickness. For stimuli moving in-depth far peripheral presentation caused more discomfort, whereas for lateral motion the central stimuli caused more discomfort. Stimuli moving in-depth led to more head movements in the anterior-posterior direction when the entire visual field was stimulated. Observers demonstrated more head movements in the anterior – posterior direction compared to the medio – lateral direction throughout the entire experiment independent of motion direction or eccentricity of the presented moving stimulus. Head movements were elicited on the same plane as the moving stimulus only for stimuli moving in-depth covering the entire visual field. A correlation showed a positive relationship between dizziness and vection duration and between general discomfort and sway. Identifying where in the visual field motion presented to an individual causes the least amount of VR sickness without losing vection and presence can guide development for Virtual Reality games, training and treatment programs.

Keywords: visual discomfort, VR sickness, virtual reality, vection, head movements, optic-flow

Introduction

Virtual reality (VR) is starting to become a part of everyday life, being readily applied in various settings such as education, rehabilitation, training as well as entertainment (e.g. Kamińska et al., 2019; Lai et al., 2019; Laver et al., 2018; Peskin et al., 2019; Tarr and Warren, 2002). One increasingly popular way to experience VR is through head mounted displays (HMDs). The advantages of HMDs are that they cover much more of the field of view (FOV) compared to desktop displays, allow for stereoscopic presentation, for more movement in the user and allow for a complete occlusion of the surrounding environment. A wider FOV and the stereoscopic presentation can increase immersion and presence (Brooks, 1999; Pausch, Proffitt and Williams, 1997; Ragan et al., 2015; Yang et al., 2012). However, HMDs can also induce discomfort in the user (Keshavarz, Hecht and Lawson, 2014; Keshavarz et al., 2015, Rebenitsch and Owen, 2016) a phenomenon commonly referred to as cybersickness (Rebenitsch and Owen), or, more generally, visually induced motion sickness (VIMS, Keshavarz et al., 2014; Kennedy, Drexler and Kennedy, 2010) . In the context of this paper the term VR sickness is used to describe adverse physiological effects experienced in VR, such as motion sickness like symptoms (e.g. nausea, disorientation, dizziness) and visual stress symptoms (e.g. headache, eye strain, difficulty focusing).

HMDs can cause a conflict between the visual and the vestibular system (Akiduki et al., 2003). In the case of conflict, visual information is believed to dominate and override vestibular signals which in turn can lead to an illusion of self-motion, a phenomenon called vection (Nakamura, 2013; Palmisano et al., 2015; Palmisano, Mursic and Kim, 2017), as well as postural instability/swaying (Akiduki et al., 2003) in the observer. Vection can improve the user's experience of VR by eliciting a more realistic sensation of self-motion through the virtual environment improving the users experience (Riecke, 2011). This positive aspects of vection can partly be explained by its strong relationship to the experience of presence in virtual environments (Weech, Kenny and Barnett-Cowan, 2019). Presence can be defined as the feeling of being part of the virtual world reacting to virtual sensations the same way as if they were experienced in the real world (Heeter, 1992). A complex relationship has also been found between the experience of presence and VR sickness, with vection being believed to be a common contributor to both (Weech, Kenny and Barnett-Cowan, 2019). In an ideal VR experience presence and vection would be maximized and VR sickness minimized.

A mismatch in sensory cues experienced in VR can pose a challenge for the maintaining postural control. The "postural instability theory" (Riccio and Stoffregen, 1991) suggests that motion sickness is the result of postural instability elicited by unfamiliar environmental conditions (e.g. Flanagan, May and Dobie, 2004; Weech, Varghese and Barnett-Cowan, 2018). Support for this notion comes from various studies finding that the degree of sway prior to the exposure to a sickness inducing environment can predict the severity of experienced motion sickness (Smart, Stoffregen and Bardy, 2002; Stoffregen and Smart, 1998). In this study sway exhibited during rather than prior to the exposure of a moving stimulus is measured in an attempt to identify its relation to the VR sickness and vection experienced for the different optic flow stimuli.

Stereoscopic display techniques can also lead to discomfort in the user due to the accommodation-vergence conflict: Accommodation is the flexion of the lenses in the eyes that is required to focus on an object even when its distance varies. Vergence is the inward rotation of the eyes to obtain a single binocular image. In the real world these two processes work together, but in stereo displays such as HMDs, these two processes do not always match. The larger this discrepancy is, the greater the possibility that the observer experiences visual discomfort, such as headache, eyestrain and nausea (Hoffman et al., 2008; Shibata, Kim and Hoffman, 2011).

In particular, motion-in-depth results in increased visual discomfort possibly due to this conflict being more prevalent for objects moving in-depth compared to objects moving laterally or static objects (Cho and Kang, 2012; Lee et al., 2011; Li, Barkowsky and Le Callet, 2014; Menozzi, 2000; Tam et al., 2012; Yano, Emoto and Mitsuhashi, 2004). The motion direction of a stimuli might not only affect the experience of VR sickness but also vection, with the effect being related to our 'exposure history' to such motion. Motion directions that are less common in active self-motion cause weaker experiences of vection (Bubka, Bonato, Palmisano, 2008). Forward motion is mostly experienced when moving through an environment hence more vection is expected for motion-in-depth compared to lateral motion. Motion-in-depth in HMDs is perceived utilizing both stereoscopic (Nefs and Harris, 2010; Nefs, O'Hare and Harris, 2010) and monocular depth-cues (Raviv and Joarder, 2000; Gonzáles et al., 2010).

The experiences of vection and VR sickness seem to be linked but their precise relationship remains unclear. Various studies suggesting a positive relationship between them (e.g. Diels, Ukai and Howarth, 2007; Flanagan May and Dobie, 2004; Moss and Muth, 2011; Palmisano et al., 2007), with vection causing or preceding the experience of VR sickness (Hettinger et al., 1990; Plouzeau et al., 2015), whilst other studies found no such relationship (Bonato et al., 2008; Keshavarz et al., 2015; Palmisano et al., 2017; Webb and Griffin, 2003).

The wider FOV in HMDs is of particular interest for vection research as the periphery of the retina is believed to be responsible for self-motion perception and spatial orientation (Brandt, Dichgans and Koenig, 1973). Directing attention to the periphery during visual motion stimulation has also been shown to increase vection whereas attending less to the central field results in decreases in vection. Performance on an attention task is better when presented in the periphery compared to the central visual field when vection is elicited simultaneously.

This suggests that more attention is directed to the periphery than the central visual field during the experience of vection (Wei, Zheng and So, 2018).

Vection increases with a wider FOV (Kim and Kim, 2019; McManus, D'Amour and Harris, 2017), with stimuli that cover a larger part of the visual field inducing a stronger feelings of vection compared to smaller stimuli (Berthoz et al., 1975; Brandt Dichgans and Koenig, 1973; Nakamura, 2006; Palmisano et al., 2017; Telford and Frost, 1993).

The exact effect of eccentricity on vection is less clear, traditionally it was believed that peripheral presentation causes stronger experiences of vection compared to central presentation (Berthoz, Pavard and Young, 1975; Brandt Dichgans and Koenig, 1973; Delorme and Martin, 1986; Johansson, 1977), but more recent research suggests that vection increases with stimulus size independent of stimulus eccentricity (Nakamura, 2001; Nakamura, 2006; Nakamura and Shimojo, 1998; Tarita-Nistor et al., 2006). The perceived depth structure of the presented stimulus could explain these discrepancies in findings. Whether motion is perceived in the background or foreground also affects the experience of vection, with motion perceived in the background being more effective in causing vection compared to motion perceived in the foreground (Delorme and Martin, 1986; Nakamura, 2006; Nakamura, 2008). The periphery being often found to be dominant over the central presentation in eliciting vection could be due to peripheral stimuli being interpreted as the background being presented behind a central mask whereas central stimuli are more likely perceived as the foreground being presented in front of the peripheral mask (Howard and Heckman, 1989).

A wider FOV also leads to more VR sickness (Duh et al., 2001; Lin et al., 2002); and reducing the FOV can lessen these adverse effects (Adhanom et al., 2020; DiZio and Lackner, 1997). Similar as for vection the effect of eccentricity on VR sickness is not as clear as the effect of FOV. The fovea is more effective in driving vergence (Stevenson, Reed and Yang,

1999) and is more sensitive to perceiving stereoscopic depth (Rawlings and Shipley, 1969) compared to the periphery. Therefore, it can be suggested that, if the conflict between accommodation and vergence is mainly responsible for causing VR sickness it would be expected that central presentation will lead to more adverse effects and that these effects are stronger for stimuli moving in-depth. The periphery is mainly believed to be responsible for postural stability and self-motion perception (e.g. Brandt Dichgans and Koenig, 1973), however, the depth level of the presented stimuli also plays a role in eliciting vection and sway, with motion perceived in the background producing more vection and sway compared to motion perceived in the foreground (Delorme and Martin, 1986). Peripheral presented stimuli are more likely to be perceived as background compared to central stimuli (Howard and Heckman, 1989).

Those findings suggest that if a sensory conflict between the visual and vestibular system is the main contributor to VR sickness peripheral presentation would lead to more adverse effects. Again, this effect is expected to be strongest for stimuli moving in-depth due to our greater experience for this direction in self-motion which enhancing the conflict between visual and vestibular inputs (Bubka, Bonato and Palmisano, 2008).

Using optic flow stimuli to simulate navigation through a large virtual environment rather than other methods, such as teleportation, enhances vection and presence and reduces disorientation, but can also cause VR sickness (Adhanom et al., 2020; Bhandari, MacNeilage and Folmer, 2018). To reduce the VR sickness caused by optic flow the FOV is often narrowed, which also reduces the observer's sense of vection (Duh et al., 2001) and presence (Cummings and Bailenson, 2016; Fernandes and Feiner, 2016; Youngblut, 2006). By varying eccentricity instead of the FOV, it may be possible to minimise VR sickness without sacrificing the sense of presence or vection. The present study will investigate the role of eccentricity systematically in optic flow stimuli in HMDs, using both motion-in-depth and lateral motion stimuli.

As well as the subjective experience of vection and VR sickness, the increased FOV of HMDs may also affect the actual movement of the observer. Swaying is based on the conflict between the visual and vestibular system (Akiduki et al., 2003) and its relation to VR sickness is discussed in the postural instability theory (Riccio and Stoffregen, 1991), with moving visual input such as expanding or contracting optic flow causing postural sway (Imaizumi et al., 2015).

A wider FOV increases sway, hence presenting a motion pattern in the full visual field is most effective in increasing sway (Duh et al., 2001; Kim and Kim, 2019). Peripheral vision is believed to play the dominant role in controlling posture (Berencsi, Ishihara and Imanaka, 2005; Brandt, Dichgans and Koenig, 1973; Delorme and Martin, 1986; Horiuchi, Ishihara and Imanaka, 2017; Kawakita et al., 2000) particularly in the anterior-posterior direction (e.g. Webb and Griffin, 2003).

The illusion of self-motion and sway are closely related, with visual motion being interpreted as self-motion, and in an attempt to compensate for this perceived self-motion a postural response is generated (Lee and Lishman, 1975). Vection is perceived in the opposite direction to the visually presented optic flow stimulus, which in turn leads to postural sway being displayed in the same plane of the presented visual stimulus (Holten, 2015; Holten et al., 2014). Head movements in anterior-posterior and medio-lateral directions were recorded in this study in order to obtain a measure of sway. In the current experiment, stereoscopic motion-in-depth cues were of particular interest, therefore monocular depth cues (looming) were minimized by choosing a relatively small size for the moving elements.

Additional influences on vection and VR sickness are the speed of the presented stimulus and eye movements (e.g. Flanagan, May and Dobie, 2004), with faster moving stimuli leading to more vection (Nakamura and Shimojo, 1999; Seya, Shinoda and Nakaura, 2015; Seya, Tsuji and Shinoda, 2014) and more VR sickness (Frey et al., 2016; Li et al., 2014). World speed translates differently to retinal speed for objects moving in-depth and objects moving laterally (Cormack et al., 2017; Lee, Ales and Harris, 2019). Therefore, perceived speed rather than actual speed was kept constant for all stimuli (based on pilot work) in this study. Rapid involuntary eye movements can lead to VR sickness in the viewer (Ebenholtz, 1992; Yang et al., 2011) with eye fixation reducing this effect (Chang et al., 2013; Duh, Parker and Furness, 2001; Stern et al., 1990). The beneficial effect of fixation depends on the type of visual stimulus presented; fixation has been shown to be particularly effective in conditions with postural challenging visual stimuli (e.g. optic flow patterns) but has contrary effects in conditions with static visual stimulation (Flanagan, May and Dobie, 2004). In addition, adding a fixation cross seems to increase vection for central presentation but does not have an effect on vection for peripheral stimulation (Tarita-Nistor et al., 2007). However, depending on the position of the fixation cross it can cause foreground or background effects influencing vection strength. In the current study a fixation cross was placed in the centre of the FOV and in the centre of the region in which the moving stimulus elements could appear to reduce effects of eye movements on VR sickness and vection (Nakamura and Shimojo, 1999).

Vection, VR sickness and sway and their relationship have been investigated intensively in the past (e.g. Holten, 2015; Palmisano et al., 2007; Plouzeau et al., 2015; Smart, Stoffregen and Bardy, 2002). However, to the best knowledge of the authors no research has looked at the effects of different motion directions and eccentricities on vection, VR sickness, sway and their relationship in this combination before. The aim of the current study was to further explore the relationship of VR sickness, vection and sway in VR. The study will investigate first the effect of motion direction (motion-in-depth compared to lateral motion) on vection and VR sickness, using a full-FOV stimulus, whilst recording head movements. Secondly, the study will systematically investigate the role of eccentricity as well as motion direction using three restricted areas: central, near peripheral, and far peripheral. VR sickness in this study was measured after each stimulus presentation with observers rating how much general discomfort, headache, dizziness, blurred vision and eye strain they experienced viewing each stimulus. Using these 5 quick measures that were obtained while the observer was still inside the VR environment resulted in separate measures of discomfort for each stimulus and thereby allowed to relate them to head movements and vection obtained for that individual stimulus. The measures have been used in previous work by the authors and were chosen based on the three subscales of the Simulator Sickness questionnaire (Kennedy et al., 1993) and on previous work using similar measures for discomfort experienced during stereoscopic presentation (Shibata, Kim and Hoffman, 2011).

For the first part of the study it was expected that vection and VR sickness will be stronger for stimuli moving in-depth compared to stimuli moving to the sides, and that head movements will follow the same plane of motion as the visual stimulus. In the second part of the study the effect of eccentricity on vection and VR sickness will be investigated while it was expected that more peripheral stimuli will cause greater head movements compared to more central ones. To allow for a clear comparison of eccentricity conditions, central, peripheral and far peripheral stimuli in this study were kept constant in regard to the area of visual stimulation, number of dots, and dot density.

Methods

Observers

Thirty-one observers with normal or corrected to normal vision took part in this study. Due to technical problems the data of 3 observers were not recorded resulting in a final sample size of 28 observers ranging in age from 19 - 26 years (M = 21.43 years, SD = 2.24). Twenty observers identified as female, 7 as male and 1 observer identifies as gender variant/non-conforming. Thirteen observers had previous experience with VR whereas the other 15 had never used VR before. Written informed consent was obtained from all observers prior to participating in the experiment and the study was approved by the University of Lincoln’s Ethics Committee. Additionally, observers were informed that they could withdraw from the study at any point and that data would be analysed anonymously. All experimental procedures adhered to the Declaration of Helsinki (2013). Individuals suffering from photosensitive epilepsy as well as pregnant individuals were excluded from the study.

Apparatus

A custom build computer with Intel i7-7700 core processor, 16GB RAM and an NVidia (GeForce GTX 1070) graphics card, running 64-bit Windows 10 was used to control the headset and run the experiment. A Valve Index headset, which completely covers the FOV of the observer was used to present the stimuli. The headset consists of two separate RGB LCD displays one for each eye with a resolution of 1440x1600 pixel and a final resolution of 2880x1600 pixel combined. Depending on the observer settings it yields a FOV of up to 130° and used the refresh rate of 120Hz in this experiment. Stimuli were presented using 64-bit Unity 2018.2 (Unity Technologies, San Francisco, USA), using the Steam platform.

Stimuli

The virtual environment was made up of a completely black surround with moving stimuli presented in the front of the observer with the fixation cross marking the centre of the FOV. The orange fixation cross (0.15units^2, ~2.02°) was presented in the centre of the visual field at a distance of 4.25 units marking the centre of the moving stimulus.

The visual stimuli were made up of three components, namely, a particle system, a mask, and the fixation cross. The particle system operated as an optic flow pattern consisting of numerous dots (~18000). The particle system was presented 1.5 units in front of the observer and had a depth of 7 units, a height of 9 units and a width of 9 units, covering the entire FOV when unrestricted. The mask was used to limit the view of the motion stimulus to either the center, periphery or far periphery. The dots within the particle system were light turquoise in colour and had a small starting size of 0.0045 units^2 (~0.03°). To keep the moving stimulus as realistic as possible both binocular and monocular depth cues were present, dots increased in size when moving closer and decreased in size when moving away from the observer. The size of the dots was chosen to be fairly small in order to minimise the looming cue to motion-in-depth (Gray and Regan, 1998; Regan and Beverley, 1979).

The dots either moved towards the observer (forward motion), away from the observer (backward motion), from the right side of the observer to the left side (left motion) or from the left side of the observer to the right side (right motion), see figure 1. Actual speed/world speed does not translate into perceived speed the same way for objects moving in depth and objects moving in the lateral plane (Lee, Ales and Harris, 2019). Perceived speed of the stimuli was kept constant, stimuli moving in the lateral plane moved at a stimulation speed of 1 units/sec whereas stimuli moving in depth moved at a speed of 1.5 units/sec, based on pilot testing.

*******************************figure 1 here *******************************

Full-field stimulus

The full-field experiment has no mask resulting in the visual motion stimuli being visible in the entire FOV.

Restricted stimuli

The mask is presented 1 unit in front of the observer and depending on the condition covers different parts of the FOV. There were three eccentricity conditions (center, the periphery, the far periphery), see figure 2. The stimuli in the three eccentricity conditions and four motion directions were kept constant in area, size, dot size and dot density, using the mask. The central condition figure 2a consisted of a mask that allows the motion stimulus to be seen through a small circle shaped opening occluding everything but the central visual field (± 20°). The mask in the peripheral condition figure 2b allows the observer to view the moving stimuli through an angular shaped opening around ± 30° (± 27° to ± 33.6°) occluding the center and the far periphery of the observer's visual field. The mask in the far periphery 2c looks similar to the one in the periphery condition with the ring-shaped opening being slightly thinner than in the periphery condition allowing the motion to be seen only in the far periphery around ±50° (± 48° to ± 52°). The area in which the motion is visible in the three eccentricity conditions is kept constant to ensure that an effect of eccentricity on vection, VR sickness or head movements is not affected by the size of the stimulus.

*****************************figure 2 here*********************************

Measures

For each stimulus, observers verbally rated the vection magnitude on a 11-point Likert scale, with 0 indicating no vection and 10 representing the strongest experience of vection. Vection onset and vection duration times were recorded by button press. Additionally, observers verbally rated their experience of general discomfort, headache, blurred vision, dizziness, and eye strain on the same 11-point Likert scale. Verbal reports were recorded by the experimenter. The Simulator Sickness Questionnaire (SSQ, Kennedy, Lane, Berbaum & Lilienthal, 1993) as well as the Motion Sickness Susceptibility Questionnaire Short Version (MSSQ-Short, Golding, 1998) were administered for an overall measure of VR sickness and to asses observer's susceptibility to motion sickness. The SSQ was administered immediately prior to and immediately after the experimental condition. The pre-session scores served as a baseline measure and were subtracted from the scores collected after the experimental condition. The scores reported are the result of the subtraction.

Head movements for x (medio-lateral) and z (anterior-posterior) co-ordinates were recorded throughout the whole experiment, using the headset readout. The data was sampled at 50Hz.

Procedure

After giving informed consent for the experiment and filling out the SSQ and the MSSQ observers were asked to stand in the centre of the experimental area wearing the headset and holding the controllers. To adjust to the virtual environment and to get used to the controllers and headset observers were allowed to play a VR-game prior to completing the task (*Spiderman: Homecoming-VR Experience* (Create VR, Sony Pictures VR, 2017)). For the duration (~ 20 min) of the experiment observers were asked to stand as still as possible. A standing rather than seating position was chosen for observers as vection has been shown to be perceived as stronger when standing compared to sitting (Kruiff et al., 2016). Observers were instructed to focus on the fixation cross presented in the centre of their visual field. The concept of vection was also explained to the observers giving the "train example" as a real-life instance of illusory self-motion. To familiarise observers with the experiment, a short training block was performed before the main experiment. The training block consisted of 5 different motion stimuli that were presented for 10 seconds in random order. The experimental block consisted of 16 stimuli that were presented for 30s each in random order. After the stimuli presentation observers were asked to verbally rate the vection magnitude of the stimulus as well as the level of VR sickness they experienced while viewing the stimulus (general discomfort, headache, blurred vision, dizziness, and eyestrain) from 0-10 with 0 meaning they experienced no VR sickness/vection. In addition, they were instructed to indicate vection onset times and the duration of vection by pressing and holding the “trigger” button. They were informed that they could press the button multiple times for one stimulus if necessary. After rating each stimulus, the researcher prompted the observer to initiate the next trial. Observers initiated the next trial by pressing the “B” button. An 8 second delay was put in place before the onset of each trial to avoid vection aftereffects and to give observers a short break after rating the stimuli. After observers finished the VR part of the study they filled out the SSQ for a second time.

Analysis

Head movement data was recorded for the x (medio-lateral) and z (anterior – posterior) coordinates of the headset for each observer for the entire duration of the experiment. These data was read into MATLAB version R2018a (Mathworks, Natick, USA) for analysis. The time sequence for the duration of each of the 16 stimuli (30s each) was extracted and the head movements for each time sequence were normalized around the point of origin. Stimuli with outlying responses were excluded from further analysis (12 out of 448). Outlying responses were calculated as followed: responses for all stimuli for each observer were pooled into a single vector for medio-lateral displacement direction (x) and one single vector for anterior –

posterior displacement direction (z), mean and standard deviations of these vectors were calculated and responses that exceeded 3 times the standard deviation from the mean of these vectors were excluded and classed as outliers. The maximum displacement in both medio-lateral (x) and anterior-posterior direction (z) with respect to each stimulus and observer were calculated.

Statistical analysis was conducted using R 1.2.5019 (R Core Team, 2019) using the “lmer” function of the *lme4* package (Bates et al., 2014) to perform a linear mixed effect analyses on the effect of eccentricity (center, periphery, far periphery) and motion direction (motion-in-depth , lateral motion) of the visual stimulus on vection magnitude, VR sickness ratings (general discomfort, headache ratings, blurred vision ratings, dizziness ratings, eye strain) and head movements (medio – lateral, anterior – posterior direction). A Welch two sample t-test was conducted to compare head movements in medio - lateral and anterior – posterior direction. Linear mixed effect models in comparison to more traditional ANOVAs have advantages in their ability to model non-linear individual characteristics and deal with missing data, additionally, they allow for multiple observations from the same observer (Krueger and Tian, 2004). For linear mixed-effects models, p-values of overall effects were determined using conditional F tests with Satterthwaite’s approximation to degrees of freedom (Satterthwaite, 1946) using a Type III ANOVA, as implemented in the “anova” function from the *lmerTest* package (Kuznetsova, Brockhoff and Christensen, 2015). Post hoc analysis was conducted using the “emmeans” function of the *cran* package (Lenth, 2017). The Tukey test was employed to further investigate the effects of the 3 levels of eccentricity as well as the interaction effects. Following the examples of Winter (2013), the model was compared to a null model missing the variable of interest using a likelihood ration test, in order to obtain a difference in Bayes Information Criterion (ΔBIC), to estimate the strength of the evidence for a particular effect. Models were created for fixed effects that showed a significant effect on the outcome variable. Additionally, based on Lorah, (2018) suggestions Cohen's f^2 was calculated for fixed effects showing a significant effect using the "r.squaredGLMM" of the *MuMIn* package (Barton and Barton, 2015) to calculate R^2 for the full an null model allowing to determine the Cohen's f^2 of the fixed effects using the following function: $f^2_{\text{significant effect}} = \frac{R^2_{full\,model} - R^2_{null\,model}}{1 - R^2_{full\,model}}$. For all the models Satterthwaite's approximation was used to adjust the degrees of freedom for violations of sphericity (Luke, 2017; Satterthwaite, 1946). Figures were produced using the "visreg" function within the *visreg* package (Breheny and Burchett, 2017).

No differences between left and right moving stimuli or backward and forward moving stimuli were detected (see Supplementary Information), therefore the four conditions were collapsed into two motion direction conditions: motion in-depth (backward and forward) and lateral motion (left and right). The full FOV condition was analysed separately, as there are several differences between the different eccentricity conditions and the full-screen condition, e.g. number of dots, dots density, size of stimulus, etc. The full FOV condition was believed to have the strongest motion effect and therefore served to compare the full effect of motion-in-depth and lateral motion on VR sickness, vection and head movements.

To investigate the relationship of VR sickness, vection and head movements a Pearson correlation was conducted using the "rcorr" function within the Hmisc package (Harrell and Harrell, 2019).

Results

Part One: Effects of motion direction in the full FOV condition (motion-in-depth vs. lateral motion)

Effects of motion direction on vection

Vection measures were predicted using linear mixed effect models, including motion direction (motion in-depth vs. lateral motion) as fixed effect and the intercept for observers as random effect. Means and Standard deviations for all measures and conditions can be found in table 1.

********************************table 1 here******************************

Vection magnitude: A significant effect of motion direction was found for vection magnitude, $F(1,83)= 50.56$, $p < .001$, $f^2 = .61$, $\Delta BIC = 35.24$. Observers experienced stronger vection for stimuli moving in-depth ($M = 7.59$, $SD = 2.16$) compared to stimuli moving to the sides ($M = 5.25$, $SD = 2.76$).

Vection Onset: No significant effect of motion direction was found for vection onset times, $F(1,61.92) = 0.07$, $p = .792$.

Vection Duration: No significant effect of motion direction was found for vection duration times, $F(1,51.81) = 1.28$, $p = .263$.

Effects of motion direction on VR sickness measures

VR sickness ratings (general discomfort, headache, eye strain, blurred vision, and dizziness) were predicted using a linear mixed effect model, including motion direction (motion in-depth vs. lateral motion) as fixed effects and the intercepts for observers as random effects.

General discomfort: A significant effect of motion direction was found for general discomfort ratings, $F(1,83) = 5.41$, $p = .022$, $f^2 = .07$, $\Delta BIC = 0.58$. Observers experienced more discomfort for stimuli moving in-depth (M = 6.18, SD = 7.58) compared to stimuli moving to the sides (M = 4.54, SD = 6.42).

Headache: No significant effect of motion direction was found for headache ratings, $F(1,83) = 0.07$, $p = .788$.

Blurred vision: No significant effect of motion direction was found for blurred vision ratings, $F(1,83) = 0.04$, $p = .836$.

*Dizziness:*A significant effect of motion direction was found for dizziness ratings, $F(1,83) = 6.15$, $p = .015$, $f^2 = .07$, $\Delta BIC = 1.29$. Observers felt dizzier for stimuli moving in-depth (M = 2.30, SD = 2.74) compared to stimuli moving to the sides (M = 1.54, SD = 2.11).

Eye strain: No significant effect of motion direction was found for eye strain ratings, $F(1,83) = 0.09$, $p = .766$.

Head movements

Medio – lateral vs. anterior – posterior direction

A Welch two sample t-test was conducted to compare head movements in medio - lateral and anterior – posterior direction. This analysis includes only the full screen condition. To ensure normal distribution of head movement data the log-transform was taken for this analysis. A significant difference for head movements was found between the medio –lateral (M = - 3.58, SD = 0.68) and anterior – posterior direction (M = - 3.00, SD = 0.43), $t(180.24) = -7.50$, $p < .001$, $d = 0.24$. Observers showed more head movements in anterior – posterior direction compared to the medio - lateral direction. See figure 3.

*****************************figure 3 here**********************************

Effects of motion direction on head movements

Head movements in medio – lateral and anterior – posterior directions were predicted using linear mixed effect models, including motion direction (motion in-depth vs. lateral motion) as fixed effects and the intercept for observers as random effect.

Residual plots were inspected and revealed heteroscedasticity in head movements, therefore the log-transform was taken. Following this transformation, no deviation from homoscedasticity or normality was observed.

Head Movements in the medio-lateral direction: No significant effect of motion direction was found for head movements in the medio – lateral direction, F(1,78.37) = 1.34, p = .250.

Head Movements in the anterior – posterior direction: A significant effect of motion direction was found for head movement in the anterior – posterior direction, F(1,79.81) = 7.57, p = .007, f^2 = .07, ΔBIC = 2.68. Observers experienced more head movements for stimuli moving in-depth (M = -2.90, SD = 0.43) compared to stimuli moving to the sides (M = -3.10, SD = 0.40). See figure 4.

*****************************figure 4 here**********************************

Part Two: Effects of eccentricity and motion direction for restricted conditions

Effects of eccentricity and motion direction on vection

Vection measures were predicted using linear mixed effect models, including motion direction (motion in-depth vs. lateral motion), eccentricity (central, periphery, far periphery) and their interaction as fixed effects and the intercept for observers as random effect.

Vection Magnitude: A significant effect of motion direction on vection magnitude was found, F(1,639) = 42.61, p < .001, f^2= .08 ,ΔBIC = 30.1. Observers rated their experience of vection stronger for stimuli moving in-depth (M = 3.24, SD = 2.38) compared to stimuli moving from side to side (M = 2.36, SD = 2.23). A marginally significant effect on vection magnitude was found for eccentricity, F(2,639) = 2.82, p = .060, f^2= .02, ΔBIC = -11.8. However, a Tukey post hoc test revealed no significant difference in vection magnitude ratings between the central (M = 2.71, SD = 2.38) and the peripheral (M = 2.66, SD = 2.16; t(639) = 0.32, p = .945, d = 0.02) and far peripheral (M = 3.03, SD = 2.48; t(639) = -1.88, p = .146, d = 0.13) conditions or between the peripheral and far peripheral conditions (t(639) = -2.20, p = .072, d = 0.16) .The interaction of eccentricity and motion direction had a significant effect on vection magnitude, F(2,639) = 4.33, p = .014, f^2= .01, ΔBIC = -4.4. Post hoc analysis revealed that Eccentricity affected vection magnitude ratings only for stimuli moving in depth but not for stimuli moving to the sides. For stimuli moving in-depth; far peripheral stimuli (M = 3.75, SD = 2.53) were rated higher compared to central (M = 2.98, SD = 2.23; t(639) = -3.26, p = .003, d = 0.32) and peripheral stimuli (M = 3.00, SD = 2.31; t(639) = -3.19, p = .004, d = 0.31). No difference was found between central and peripheral stimuli (t(639) = -0.08, p = .997, d = 0.01). For stimuli moving to the sides; no significant difference between stimuli presented in the central (M = 2.45, SD = 2.50) and peripheral (M = 2.32, SD = 1.96; t(639) = 0.53, p = .856, d = 0.06) and far peripheral (M = 2.30, SD = 2.20; t(639) = 0.61, p = .816, d = 0.06) FOV were found. Additionally, no difference were found between peripheral and far peripheral stimuli (t(639) = 0.08, p = .997, d =0.01). See, figure 5.

******************************figure 5 here************************************

Vection Onset: No significant effects on vection onset times were found for eccentricity ($F(2,385.95) = 0.05$, $p = .947$) motion direction ($F(1,385.21)= 0.16$, $p = .689$) or the interaction of eccentricity and motion direction ($F(2, 385.79)= 0.26$, $p = .768$).

Vection Duration: There was a significant effect of eccentricity on vection duration, $F(2, 381.45) = 3.24$, $p = .040$, $f^2=.02$, $\Delta BIC = -17.5$. A Tukey post hoc test revealed that stimuli presented in the periphery (M = 8.61s, SD = 7.85s) let to marginally significantly shorter vection duration times compared to central (M = 10.31s, SD = 9.09s; $t(382) = 2.23$, $p = .068$, $d = .20$) and far peripheral stimuli (M = 10.42s, SD = 9.39s; $t(382) = -2.28$, $p = .060$, $d = 0.21$). No difference in vection duration time was found for central and far peripheral stimuli ($t(382) = -0.05$, $p = .999$, $d = 0.01$). No significant effects on vection duration were found for motion direction ($F(1, 380.83) = 2.10$, $p = .148$) or the interaction of eccentricity and motion direction($F(2,381.36)=0.07$, $p = .934$).

Effects of eccentricity and motion direction on VR sickness measures

VR sickness ratings (general discomfort, headache, eye strain, blurred vision, and dizziness) were predicted using a linear mixed effect model, including motion direction (motion in-depth vs. lateral motion), eccentricity (central, periphery, far periphery) and their interaction as fixed effects and the intercepts for observers as random effects.

General discomfort: No significant effect of motion direction ($F(1,639) = 1.21$, $p = .27$) or eccentricity ($F(2,639) = 1.34$, $p = .263$) was found for general discomfort ratings. A significant effect on general discomfort ratings was found for the interaction of eccentricity and motion direction, $F(2,639) = 10.17$, $p <.001$, $f^2 =.03$, $\Delta BIC = 7.2$. Post hoc analysis revealed that for stimuli moving in depth; stimuli presented in the far periphery (M = 0.61, SD = 1.21) were rated higher on discomfort compared to stimuli in the centre (M = 0.23, SD = 0.73; t(639) = -2.86, p = .01, d = 0.38). No differences were found between stimuli presented in the periphery (M = 0.39, SD = 1.02) and the centre (t(639) = -1.22, p = .440, d = 0.18) and the far periphery (t(639) = -1.63, p = .233, d = 0.20). For laterally moving stimuli; central stimuli (M = 0.79, SD = 1.82) caused significantly more discomfort compared to peripheral (M = 0.34, SD = 0.99; t(639) = 3.40, p = .002, d = 0.31) and far peripheral stimuli (M = 0.36, SD = 0.88; t(639) = 3.26, p = .003, d = 0.30). No difference was found between peripheral and far peripheral stimuli (t(639) = -0.14, p = .990, d = 0.02). See figure 6a.

Headache: Marginally significant effects on headache ratings were found for motion direction (F(1,639) = 2.97, p = .085, f^2 = .02, ΔBIC = -5.9) and eccentricity (F(2,639) = 2.62, p = .074, f^2 = .03, ΔBIC = -10.2). Observers experienced more headache for stimuli moving in-depth (M = 0.61, SD = 1.50) compared to stimuli moving to the sides (M = 0.48, SD = 1.46). Post hoc analysis revealed no difference in headache ratings between stimuli presented in the central (M = 0.58, SD = 1.42) and the peripheral (M = 0.43, SD = 1.33; t(639) = 1.63, p = .233, d = 0.11) and the far peripheral (M = 0.63, SD = 1.68; t(639) = -0.58, p = .833, d = 0.3) condition or between the peripheral and far peripheral conditions (t(639) = -2.21, p = .071, d = 0.13). A significant effect on headache ratings was found for the interaction of eccentricity and motion direction, F(2,639) = 5.34, p <.001, f^2 = .02, ΔBIC = -2.4. For stimuli moving in depth; stimuli presented in the far periphery (M = 0.86, SD = 1.83) were rated higher on headache compared to stimuli in the centre (M = 0.50, SD = 1.23; t(639) = -2.71, p = .019, d = 0.23) or periphery (M = 0.48, SD = 1.37; t(639) = -2.85, p = .013, d = 0.24). No differences between central and peripheral stimuli (t(639) = 0.14, p = .990, d = 0.02) was found. For stimuli moving to the sides; no significant difference between stimuli presented in the central (M = 0.66, SD = 1.58) and peripheral (M = 0.38, SD = 1.30; t(639) = 2.17, p = .077, d = 0.19) and far peripheral (M = 0.41, SD = 1.49; t(639) = 1.90, p = .140, d = 0.16) FOV were found.

Additionally, no difference were found between peripheral and far peripheral stimuli ($t(639) = -0.27$, $p = .960$, $d = 0.02$). See figure 6b.

Blurred vision: A significant effect of motion direction on blurred vision ratings was found, $F(1,639) = 5.17$, $p = .023$, $f^2 = .02$, $\Delta BIC = -8$. Observers experienced increased blurred vision for stimuli moving to the sides ($M = 0.90$, $SD = 1.91$) compared to stimuli moving in-depth ($M = 0.70$, $SD = 1.65$). No significant effect of eccentricity on blurred vision was found, $F(2,639) = 0.51$, $p = .601$. A significant interaction between motion direction and eccentricity was found. $F(2,639) = 3.22$, $p = .041$, $f^2 = .01$, $\Delta BIC = -6.6$. Post hoc analysis revealed that for stimuli moving in depth; no significant difference between stimuli presented in the central ($M = 1.09$, $SD = 1.98$) and peripheral ($M = 0.91$, $SD = 1.98$; $t(639) = 0.11$, $p = .993$, $d = 0.09$) and far peripheral ($M = 0.71$, $SD = 1.76$; $t(639) = -1.13$, $p = .500$, $d = 0.20$) FOV were found. Additionally, no difference were found between peripheral and far peripheral stimuli ($t(639) = -1.24$, $p = .432$, $d = 0.11$). For laterally moving stimuli; central stimuli ($M = 1.09$, $SD = 1.98$) caused significantly more blurred vision compared to far peripheral stimuli ($M = 0.71$, $SD = 1.76$; $t(639) = 2.36$, $p = .048$, $d = 0.20$). No difference was found between peripheral ($M = 0.91$, $SD = 1.98$) and central ($t(639) = 1.13$, $p = .499$, $d = 0.09$) and far peripheral stimuli ($t(639) = 1.24$, $p = .432$, $d = 0.11$). See figure 6c.

Dizziness: A marginally significant effect of eccentricity on dizziness ratings was found, $F(2,639) = 2.91$, $p = .055$, $f^2 = .03$, $\Delta BIC = -5.7$. However, a Tukey post hoc test revealed no significant difference in dizziness ratings for stimuli presented in the center ($M = 0.91$, $SD = 1.74$) compared to stimuli presented in the periphery ($M = 0.79$, $SD = 1.64$; $t(639) = 0.88$, $p = .656$, $d = 0.07$) or far periphery ($M = 0.69$, $SD = 1.52$; $t(639) = 0.88$, $p = .656$, $d = 0.13$) or between the peripheral and far peripheral conditions ($t(639) = 0.00$, p =. 0.999, $d = 0.06$). No significant effect of motion direction on dizziness ratings was found, $F(1,639) = 0.02$, $p = .875$. A significant effect on dizziness ratings was found for the interaction of eccentricity and motion direction, $F(2,639) = 7.33$, $p < .001$, $f^2 = .02$, $\Delta BIC = 1.6$. Post hoc analysis revealed that for stimuli moving in depth; no significant difference between stimuli presented in the central (M = 1.11, SD = 2.04) and peripheral (M = 0.71, SD = 1.61; $t(639) = -1.23$, $p = .438$, $d = 0.22$) and far peripheral (M = 0.55, SD = 1.38; $t(639) = -0.82$, $p = .692$, $d = 0.32$) FOV were found. Additionally, no difference were found between peripheral and far peripheral stimuli ($t(639) = 0.41$, $p = .912$, $d = 0.11$). For laterally moving stimuli; central stimuli (M = 1.11, SD = 2.04) caused significantly more dizziness compared to peripheral (M = 0.71, SD = 1.61; $t(639) = 3.00$, $p = .008$, $d = 0.22$) and far peripheral stimuli (M = 0.55, SD = 1.38; $t(639) = 4.23$, $p < .001$, $d = 0.32$). No difference was found between peripheral (M = 0.91, SD = 1.98) and far peripheral stimuli ($t(639) = 1.23$, $p = .438$, $d = 0.11$). See figure 6d.

Eye strain: No significant effect on eye strain ratings was found for motion direction ($F(1,639) = 2.17$, $p = .141$) or eccentricity ($F(2,639) = 2.10$, $p = .123$). A significant effect on eye strain ratings was found for the interaction of eccentricity and motion direction, $F(2,639) = 4.47$, $p = .012$, $f^2 = .01$, $\Delta BIC = -4$. Post hoc analysis revealed that for stimuli moving in depth; far peripheral (M = 0.86, SD = 1.91) stimuli caused significantly more eye strain compared to central stimuli (M = 0.38, SD = 1.07; $t(639) = -3.45$, $p = .002$, $d = 0.31$). No difference was found between peripheral (M = 0.57, SD = 1.39) and central ($t(639) = -1.40$, $p = .340$, $d = 0.15$) and far peripheral stimuli ($t(639) = -2.04$, $p = .103$, $d = 0.17$). For laterally moving stimuli; no significant difference between stimuli presented in the central (M = 0.80, SD = 1.74) and peripheral (M = 0.66, SD = 1.76; $t(639) = 1.02$, $p = .564$, $d = 0.08$) and far peripheral (M = 0.70, SD = 1.75; $t(639) = 0.77$, $p = .724$, $d = 0.06$) FOV were found. Additionally, no difference were found between peripheral and far peripheral stimuli ($t(639) = -0.26$, $p = .965$, $d = 0.02$). See figure 6e.

Eccentricity appears to have an opposite effect on discomfort ratings for the two motion direction. discomfort increases with eccentricity for stimuli moving in-depth whereas for stimuli moving to the sides a reverse trend can be found.

*****************************figure 6 here*********************************

Head movements

Medio – lateral vs. anterior – posterior direction

A Welch two sample t-test was conducted to compare head movements in medio - lateral and anterior – posterior direction. This analysis includes all three eccentricity conditions. To ensure normal distribution of head movement data the log-transform was taken for this analysis. A significant difference for head movements was found between the medio –lateral ($M = -3.70$, $SD = 0.68$) and anterior – posterior direction ($M = -3.14$, $SD = 0.40$), $t(534.89) = -13.02$, $p < .001$, $d = 0.07$. Observers showed more head movements in anterior – posterior direction compared to the medio - lateral direction.

Effects of eccentricity and motion direction on head movements

Head movements in medio – lateral and anterior – posterior directions were predicted using linear mixed effect models, including motion direction (motion in-depth vs. lateral motion), eccentricity (central, periphery, far periphery) and their interaction as fixed effects and the intercept for observers as random effect.

Residual plots were inspected and revealed heteroscedasticity in head movements, therefore the log-transform was taken. Following this transformation, no deviation from homoscedasticity or normality was observed.

Head movements in the medio – lateral direction: No significant effects on head movements in the medio-lateral direction were found for motion direction ($F(1, 295.17) = 0.141$, $p = .708$), eccentricity ($F(2,295.17) = 0.16$, $p = .855$) or their interaction ($F(2, 295.17) = 0.670$, $p = .499$).

Head movements in the anterior – posterior direction: No significant effects on head movements in the anterior-posterior direction were found for motion direction ($F(1, 295.21) = 1.74$, $p = .189$), eccentricity ($F(2,295.21) = 1.20$, $p = .303$) or their interaction ($F(2, 295.20) = 0.40$, $p = .668$).

Part Three: Correlation of VR sickness ratings, vection magnitude ratings and head movements

A Pearson correlation was conducted to investigate the relationship between VR sickness, vection and head movements (log -transformed). Pearson's r and significance values can be found in table 2. Headache, dizziness, blurred vision and eye strain ratings showed a strong positive correlation with each other. Dizziness ratings showed a moderate positive correlation with vection duration times. Vection duration was positively correlated with vection magnitude and negatively with vection onset times. Discomfort ratings showed a positive moderate relationship with head movements in the anterior-posterior direction and MSSQ scores showed a negative moderate correlation with head movements in the medio-lateral direction.

**************************table 2 here*************************************

Discussion

The main aim of this experiment was to investigate the effects of motion direction and eccentricity of optic flow stimuli on the experience of vection, VR sickness and head movements. Therefore, moving dot stimuli were presented in a virtual environment with observers rating the strength of experienced vection magnitude, general discomfort, headache, blurred vision, dizziness and eye strain for each stimulus, whilst also indicating at what time points during presentation they experienced vection. Head movements were recorded in medio-lateral and anterior-posterior directions for each stimulus.

Vection

In both the full FOV and the restricted conditions, visual stimuli moving in-depth caused a stronger illusion of self-motion compared to laterally moving stimuli. According to Bubka and colleagues (2008) these differences could partially be explained based on the sensory conflict theory. In their study they compared expanding and contracting optic flow patterns finding stronger vection for expanding patterns simulating forward self-motion. They suggest that a more extensive experience with forward self-motion might form stronger expectancies about the non-visual sensory inputs that typically accompany the expanding flow pattern. When only presented with visual stimulation the conflict between the sensory systems is greater for more commonly experienced self-motions directions. Vection occurs when sensory inputs are inconsistent with an individual's 'exposure history', when only some of the sensory inputs (typically visual) that accompany self-motion are present. A stronger inconsistency between an individual's 'exposure history' and the presented sensory stimulation leads to stronger vection (Bubka, Bonato and Palmisano, 2008). This theory might partly explain the findings in this study, given that forward and backward self-motion (particularly forward) are more common than lateral motion. We are more likely to have a stronger 'exposure history' for walking back and forth than walking to the sides (left and right). However, the current study could not find significant differences between simulated forward and backward self-motion contradicting Bubka and colleagues' findings and the notion of exposure history influencing the experience of vection, therefore this theory is insufficient to account for all the results.

Alternatively, the dominance of stimuli moving in-depth could be explained by visual and vestibular cue combination. Traditionally visual cues are believed to be dominant and override vestibular cues when experiencing vection. Butler and colleagues however, found that more weight is given to the vestibular information when judging heading direction in situation in which a conflict between the visual and vestibular information exist (Butler and Campos, 2015; Butler et al., 2010). Observers in this study showed more head movements in the anterior- posterior compared to the medio-lateral direction throughout the experiment, suggesting that vestibular cues are stronger for forward and backward motion than motion to the sides. Increased vection in the motion in-depth condition found in this study could therefore support the notion of vestibular cues being weighted higher compared to visual cues in sensory conflict conditions.

The effect of eccentricity on vection magnitude is particularly prevalent for stimuli moving in-depth, with more peripheral stimuli causing stronger vection, whereas vection experienced for laterally moving stimuli seems to be less affected by which area of the visual field is stimulated, showing only a small trend for central stimuli causing a stronger feeling of self-motion. Concluding that, when the size of the presented stimulus is kept constant for the various eccentricity conditions, thereby eliminating effects on vection caused by the size of the stimulus, the motion direction of the stimulus modulates the effect of eccentricity.

According to Nakamura (2006, 2008) the perceived stimulus depth structure rather than the eccentricity of the presented stimulus can explain the dominance of the periphery in eliciting the illusion of self-motion. Moving stimuli that are perceived as the background are interpreted as self-motion whereas stimuli perceived as the foreground are more likely seen as object motion and do not cause vection. Central stimuli are more likely perceived as the foreground moving in front of a static background mask whereas peripheral stimuli are more often perceived as the background being presented behind a central mask (Howard and Heckman, 1989). The dominance of the peripheral visual field in eliciting vection for stimuli moving in-depth found in this study could therefore, either be explained by a dominance of the periphery for self-motion over the central visual field or by the perceived depth structure of the peripheral and central stimuli. However, these theories cannot explain the differences in eccentricity effects found between lateral moving stimuli and stimuli moving in-depth. Observers in this study were not asked whether they perceived the moving stimuli as background or foreground which should be included in future research to allow for a accurate investigation in the effect of eccentricity.

A possible explanation for this oppositional effect of eccentricity on vection found for stimuli moving in-depth and laterally moving stimuli could be a difference in the perceptual interpretation of the perceived motion. Stimuli moving in-depth could have been interpreted as the observer moving through a stationary environment (exocentric motion perception) whereas laterally moving stimuli could have been perceived as the environment moving around the observer (egocentric motion perception), which could explain the overall stronger vection experienced for stimuli moving-in-depth compared to laterally moving stimuli. However, observers were not asked if they experienced the optic flow patterns as self-motion or object motion, therefore, it can only be speculated that lower vection ratings for laterally moving stimuli are based on interpretation of the perceived motion. Exocentric motion perception is dominant in the periphery, whereas egocentric motion perception is more prevalent for more central areas (Brandt, Dichgans and Koenig, 1973; Berthoz, Pavard and Young, 1975), if motion in-depth was more often perceived as self-motion compared to lateral motion this could possibly explaining why eccentricity mainly affected stimuli moving in-depth, increasing vection for motion presented in the periphery compared to the central visual field. These findings suggest that the motion direction of the presented stimulus could influence the effect of eccentricity on vection and might help explain contradictions about the role of eccentricity on vection found in previous research, as different types of visual motion were presented in various studies. Some studies displayed rotating motion (e.g. Brandt, Dichgans and Koenig, 1973), others lateral motion (e.g. Nakamura, 2006; Tarita-Nistor et al., 2006) and some displayed stimuli moving in-depth (e.g. McManus, D'Amour and Harris, 2017).

In contrast, motion direction and the eccentricity of the presented stimuli did not affect the duration or onset time of vection. This contradicts previous research that found increases in vection magnitude correlating with shorter vection onset times and longer vection duration (e.g. Bubka, Bonato and Palmisano, 2008; Keshavarz et al., 2017; Riecke et al., 2006). It can be speculated that this contradiction in findings might be due to different display types being used for stimulus presentation. Stimuli in this study were presented using a HMD completely occluding the observer's surrounding, whereas other studies have used (curved) projectors or different types of desktop set ups to present their stimuli (Keshavarz et al., 2017; Riecke et al., 2006). Another cause for these contradictory findings might be the observer's position, in the current study observers were standing up, whereas other studies had their observers in a seated position (e.g. Bubka, Bonato and Palmisano, 2008; Keshavarz et al., 2017; Riecke et al., 2006). Alternatively, the three vection measures of vection used in this study (vection magnitude, onset, duration) could represent different aspects and processes involved during vection suggesting that motion direction and eccentricity of presented visual stimuli modulate the magnitude of the experienced vection but do not affect when and for how long this sensation is experienced (Seno et al., 2017).

VR sickness

The effect motion direction of an optic flow stimulus had on VR sickness varied depending on what aspect of VR sickness was investigated. For example, when the motion is displayed in the entire FOV, motion in-depth caused more dizziness and general discomfort compared to lateral motion. However, these effects have to be interpreted with caution. Cohen’s f2 indicates small effects and the differences in BIC values are very small, indicating only weak evidence for the alternative hypothesis. When parts of FOV were restricted, there were some tentative findings for headache and blurred vision, however, given that Cohen’s f2 indicated small effects and the BIC values were negative, this result should be interpreted with caution. VR sickness experienced in the current study was rated fairly low over all which could partly be explained by the short presentation time of each stimulus. Observers viewed each optic flow pattern for 30s and then rated the amount of VR sickness they experienced. VR sickness does develop over time (Kennedy, Stanney and Dunlap, 2000) and a 30s interval might not have been enough to generate a strong enough sensation of VR sickness. In future research a longer presentation time should be considered as well as multiple presentations of each trial to completely rule out order and carry over effects.

The current study used a fixation cross throughout presentation. Adding a fixation cross to the moving stimuli in this study could have minimized the difference in accommodation-vergence conflict between the two motion directions. Observers had to fixate on the cross throughout the presentation of the moving pattern, and so fixing accommodation to that point and thereby minimizing the change in accommodation-vergence conflict. These findings suggest that the accommodation-vergence conflict seems to be the driving force in the differences in VR sickness found for stimuli or objects moving in-depth and laterally moving objects.

For all VR sickness measures, the effect of eccentricity seems to be dependent on the motion direction of the visual stimulus. For stimuli moving in-depth the far peripheral condition generally seems to cause more VR sickness compared to the more central ones, and for stimuli moving to the sides the opposite effect can be found. The different effects eccentricity has on VR sickness for the two motion directions is similar to the effects on vection magnitude and therefore might be explained similarly with a dominant role of the periphery for the perceived visual-vestibular conflict. FOV has been shown to affect the experience of VR sickness with a reduction of FOV (a more central presentation) causing less VR sickness compared to a wider FOV (Duh et al., 2001; Lin et al., 2002). This technique has been widely used to improve the experience of player navigation in VR games with a FOV reduction occurring when the player moves quickly from one spot to the next which is visualised by moving the entire visual scene around the observer using optic flow cues (Adhanom et al., 2020). The results of this study indicate that this technique might be more effective when the player moves back and forth through the environment. For player movement to the sides the results of this study would recommend an occlusion of the central visual field rather than the peripheral as VR sickness was rated highest in the central condition for stimuli moving to the left or right.

The phenomenon of VR sickness that is experienced when using HMDs or other stereoscopic displays is described using numerous terms, such as *cybersickness* (Keshavarz et al., 2015), *(visually induced) motion sickness* (Keshavarz, Hecht and Lawson, 2014), *simulator sickness* (Brooks et al., 2010), or simply, (*visual) discomfort* (Lambooij et al., 2009). Hence it comes as no surprise that this phenomenon describes even more diverse symptoms. It describes anything from oculomotor symptoms, such as eye strain, headaches or blurred vision to motion sickness like symptoms such as nausea, dizziness, vertigo or stomach awareness. Therefore, to better understand VR sickness the various aspects of discomfort should be studied discretely.

Head movements

Throughout the entire experiment observers showed more head movements in the anterior – posterior direction compared to the medio – lateral direction, meaning they swayed more back and forth than to the sides independent of what stimulus was presented to them. This is in line with previous research which has found that in general during quiet upright stance sway in the anterior-posterior direction exceeds sway in the medio-lateral direction (Valles et al., 2006; Winter, 2009). Investigating cortical activity for voluntary postural sway has found that medio-lateral sway is more difficult and energy demanding compared to anterior- posterior sway which might explain this effect (Slobounov et al., 2008). Additionally in the full FOV condition, for stimuli moving in depth, there were increased head movements in the anterior-posterior direction compared to the medio-lateral direction, but no such effect on head movements was found for stimuli moving to the sides (lateral motion) or in restricted conditions. Head movements were only affected by the motion of visual stimulation presented when the full FOV was covered by the moving stimulus, possibly as the motion signal perceived in the restricted conditions might not have been strong enough to elicit head movements related to the visual stimulus. When observers viewed an optic flow pattern moving in depth, they themselves elicited more head movements in the anterior-posterior direction. No such effect was found for stimuli moving to the sides. These results do not completely align with previous research, as postural sway is generally displayed in the same plane direction of the presented stimulus (Holten, 2015; Holten et al., 2014). Based on the postural instability theory sway is believed to be partly voluntary and partly automatic with individuals eliciting less sway when instructed to hold still (Stoffregen et al., 2006). Observes in this study were instructed to hold their head as still as possible possibly resulting in them eliciting less head movements as they would have in a free viewing condition.

The peripheral visual field is believed to be mainly responsible for controlling posture and motion perceived in this area causes increased sway (Brandt, Dichgans and Koenig, 1973;

Berencsi, Ishihara and Imanaka, 2005; Hoiuchi, Ishihara and Imanaka, 2017; Kawakita, Kuno, Miyake, & Watanabe, 2000). No such effect was found in this study; central, peripheral and far peripheral stimuli all caused head movements of similar magnitude. It is possible that the area of the moving stimulus presented in the restricted conditions was not big enough to elicit a strong enough motion signal resulting in these head movements. Previous studies generally occluded either the central or peripheral visual field which should still result in fairly large areas of stimulation whereas the peripheral stimuli presented in this study were angular shaped occluding both the more central and the more peripheral areas.

A difference in findings might also be partially explained by the different tools used for measuring postural stability and sway in observers. Postural stability has for example been measured by attaching sensors to the head, torso and hip (Kim & Kim, 2019), by using force plates (Jansen, Larsen and Olesen, 1982; Levin, Mizrahi and Shoham, 1998), Swaymeters (Sturnieks, Arnold and Lord, 2011), or by measuring head movements using HMDs as sensors (Cooper et al., 2018). It can be hypothesized that each of these tools measures slightly different aspects of sway and comes with advantages and disadvantages, for example according to Sturnieks and colleagues (2011) Swaymeters are less expensive and easier to use compared to force plates but might also be less precise in their measures. HMDs are a convenient tool to measure sway experienced in a virtual environment and allow additional recordings of yaw, pitch and roll motions but might not be directly comparable to force plate measures due to different mechanisms being involved in head stabilization and foot stabilization (Peterson and Richmond,1988).

Relationships between vection, VR sickness and head movements

The relationship of vection and VR sickness has been shown to be fairly complex in various studies (e.g. Hettinger et al., 1990; Palmisano et al., 2007). The findings of this study aim to further the understanding the complex relationship of vection, VR sickness and sway. The results suggest that the relationship of the three phenomena depend on what symptoms of VR sickness are investigated. Dizziness showed a moderate positive relationship with vection duration whereas the other measures of VR sickness did not show any relationship to vection. Visual stimulation that made observers feel self-motion for a longer period of time also caused more dizziness and stimuli. Visual stimulation that caused more general discomfort in the observer led to more head movements in the anterior-posterior direction, supporting the postural instability theory. MSSQ scores however, showed a negative relationship with head movements in the medio-lateral direction. Observers that were more susceptible to experience motion sickness in every day life swayed less to the sides when in VR.

Surprisingly, the overall SSQ scores and the individual discomfort ratings collected throughout the study showed no relationship with each other. The individual ratings were based on items within the SSQ scale and therefore a positive relationship between the scale and the ratings was expected. This difference might be partially explained by the timing of measurement. Individual discomfort ratings were collected multiple times throughout the study during which observers were immersed in the virtual environment, whilst the SSQ was filled out before and after the VR session. The discomfort ratings could be measuring a subjective experience of VR sickness symptoms that is short-lived and only experienced while immersed in VR and not afterwards. Similarly, MSSQ scores were not related with any of the other discomfort measures, suggesting that an individual's motion sickness susceptibility to experiences in the real world might not be suitable to predict or is even related to VR sickness experience in a virtual environment.

Contradictory to expectations (Holten et al., 2014) vection was not related to head movements. The amount an observer felt like they were moving while viewing the motion patterns was not significantly correlated to their actual physical movement. Again, this could be due to the motion signals particularly in the restricted conditions not being strong enough to elicit head movements related to the visual stimulus, suggesting that weaker motion signals can be used to elicit vection without causing sway in the user of HMDs.

Additionally, the findings of this study suggest that the experience of vection and VR sickness is linked in some way due to a similar trend being found for the interaction of eccentricity and motion direction. A stronger experience of both VR sickness and vection was found for a more peripheral presentation of stimuli moving in-depth whereas stronger experience of the two phenomena was found for a more central presentation for laterally moving stimuli. However, it is apparent that the two were interpreted differently by observers in this experiment, shown in the different patterns of results for the two motion directions with vection being significantly stronger for stimuli moving-in-depth, whereas for VR sickness no clear differences between the two motion directions were found.

Implications

Identifying where in the visual field motion presented to an individual causes the least amount of VR sickness has various implications for example for game development or for the development of training or treatment programs. To achieve optimal training or treatment outcomes for programs presented in VR the user should feel as strongly immersed/present in the environment as possible (for a review see; Wallach et al., 2011). This also applies to video games to achieve the best game play experience (Shafer, Carbonara and Popova, 2011; Skalski et al., 2011). Player navigation throughout a virtual environment can be subject to both a loss of presence and VR sickness depending on the type of navigation used. When moving around in a small virtual environment, users can physically walk around with the view-point being updated using positional tracking. This form of locomotion offers the highest presence and rarely leads to adverse feelings as no conflict between the visual and vestibular system occurs (Usoh et al., 1999). In larger virtual environments this form of locomotion is not possible anymore due to limited available positional tracking space. Here, users can navigate through the environment either using the controllers to teleport from one point to another or by moving the entire visual scene around the observer using optic flow cues (Adhanom et al., 2020). Teleportation invokes less VR sickness but can lead to spatial disorientation (Bhandari, MacNeilage and Folmer, 2018) and a loss of presence (Bowman, Koller and Hodges, 1997) in the user which can have a negative impact on game play, learning or treatment outcomes. Using optic flow cues on the other hand can reduce the effect of disorientation and loss of presence but causes more VR sickness in the observer (Bhandari et al., 2018). A widely used method to reduce discomfort caused by optic flow is decreasing the FOV to exclusively central stimulation during such locomotion, but this method can also reduce the observer's sense of presence in the virtual environment (Cummings and Bailenson, 2016; Fernandes and Feiner, 2016; Youngblut, 2006). According to the findings of this study FOV restriction to reduce discomfort during fast locomotation is most effective during forward or backward movement, whereas an occlusion of the central visual field is believed to be more efficient during sideways motion. However, occluding parts of the visual field has also been found to lead to a loss in vection and presumably presence (e.g. Cummings and Bailenson, 2016; Duh et al., 2001). This has resulted in VR developers having to make compromises when designing applications. For example by developing a very realistic game play utilizing the entire FOV, and so increasing vection and presence, but likely causing adverse symptoms in the user. Alternatively, developers could use designs that will occlude parts of the visual field, causing less VR sickness but also limiting vection, presence and the amount of information received by the user. The effect of different FOV occlusion on presence, vection and VR sickness should be further studied to enable development of VR applications with best treatment/training outcomes and VR games allowing for a more pleasant and realistic gamer experience.

Conclusion

The effect eccentricity has on VR sickness and vection experienced in VR seems to be dependent on the motion direction of the presented stimuli. The periphery appears to be dominant in eliciting vection and VR sickness for stimuli moving in-depth, whereas central vision seems to play a bigger role for the experience of vection and VR sickness for stimuli moving to the sides. In general, motion-in-depth caused stronger feelings of illusory self-motion compared to lateral motion. Additionally, motion-in-depth stimuli were associated with increased head movements in the anterior-posterior direction. However, for a visually presented stimuli to affect head movements a strong motion signal is necessary, in this case using the entire FOV. Identifying what area to restrict to minimise VR sickness when presenting optic flow patterns can guide the development of player navigation through virtual environments causing less spatial disorientation or loss of presence.

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Conflict of interest

The authors have no conflict of interest financial or otherwise to declare.

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Figure and Table Captions

Figure 1: Optic flow diagrams for the four motion directions. A and B displaying the lateral motion conditions: right (a) and left (b). C and D representing the motion in depth conditions: forward/expanding (c) and backward/contracting (d)

Figure 2: The four display conditions with an orange fixation cross in the centre of the visual field. The mask outlines are shown in orange, please note that in the experiment the mask had no outline and was the same colour as the background. A displaying the circle shaped central condition ± 20°, B displaying the angular shaped peripheral condition ± 30°, C displaying the angular shaped far peripheral condition ± 50° and D displaying the full FOV condition.

Figure 3: Box plot showing the effects of motion direction (motion in-depth vs. lateral motion) on head movements in the anterior – posterior direction for the full FOV conditions.

Figure 4: Predicted head movements in the anterior-posterior direction for stimuli moving in depth and laterally moving stimuli in the full FOV condition. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals.

Figure 5: Predicted vection magnitude ratings for stimuli moving in depth and laterally moving stimuli for central, peripheral and far peripheral presentation. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals. Red lines represent stimuli moving in depth and blue lines represent stimuli moving from side to side.

Figure 6: Predicted a) general discomfort b) headache c) blurred vision d) dizziness e) eye strain ratings for stimuli moving in depth and laterally moving stimuli for central, peripheral and far peripheral presentation. Visualisation of the Regression model with residual plots

based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals. Red lines represent stimuli moving in depth and blue lines represent stimuli moving from side to side.

Table 1: Means and Standard deviations for the 5 VR sickness measures (general discomfort, headache, blurred vision, dizziness, eyestrain), the 3 vection measures (vection magnitude, onset, duration) and the head movement displacement (medio – lateral, anterior – posterior) for the full FOV condition and the three Eccentricity conditions.

Table 2: Pearson correlation of discomfort ratings (general discomfort, headache, blurred vision, dizziness, eye strain), vection magnitude ratings, vection onset times, vection duration times, SSQ scores, MSSQ scores and head movements (medio-lateral and anterior-posterior direction)

Table1

	Full FOV Condition		Eccentricity Conditions	
		Central	Peripheral	Far Peripheral
General Discomfort	1.07 (2.12)	0.51 (1.41)	0.37 (1.00)	0.48 (1.06)
Headache	0.72 (1.64)	0.58 (1.42)	0.43 (1.33)	0.63 (1.68)
Blurred Vision	0.79 (1.82)	0.87 (1.71)	0.77 (1.77)	0.77 (1.88)
Dizziness	1.92 (2.46)	0.91 (1.74)	0.79 (1.64)	0.69 (1.52)
Eye Strain	0.85 (1.78)	0.59 (1.46)	0.62 (1.59)	0.78 (1.83)
Vection	6.42 (2.73)	2.71 (2.38)	2.66 (2.16)	3.03 (2.47)
Vection Onset	5.40s (5.09s)	7.11s (6.91s)	6.89s (6.15s)	7.31s (7.58s)
Vection Duration	11.12s (8.31s)	10.31s (9.09s)	8.61s (7.85s)	10.42s (9.39s)
Medio – lateral HM	3.60cm (3.20cm)	3.18cm (3.09cm)	3.09cm (2.52cm)	3.12cm (2.60cm)
Anterior – posterior HM	5.45cm (2.55cm)	4.70cm (1.94cm)	4.66cm (2.02cm)	4.54cm (2.14cm)

Table 2

	General Discomfort	Headache	Blurred Vision	Dizziness	Eye Strain	SSQ	MSSQ	Vection Magnitude	Vection Onset	Vection Duration	Medio - Lateral HM
Headache	.20	-									
Blurred Vision	.23	.90***	-								
Dizziness	.33	.74***	.78***	-							
Eye Strain	.16	.87***	.96***	.80***	-						
SSQ	-.11	-.20	-.08	-.17	-.08	-					
MSSQ	-.24	-.02	-.07	.01	-.01	.24	-				
Vection Magnitude	.03	.12	.17	.27	.11	-.12	-.07	-			
Vection Onset	-.07	-.04	-.04	-.15	-.08	.07	-.04	-.05	-		
Vection Duration	.09	.28	.22	.40*	.19	-.14	.01	.55**	-.42*	-	
Medio - Lateral HM	.28	-.04	-.06	.00	-.12	-.14	-.47*	-.11	.03	.16	-
Anterior - Posterior HM	.45*	-.07	-.06	.04	.12	-.09	-.21	-.15	.24	-.22	.53**

*p < .05. **p < .01. ***p < .001, degrees of freedom = 26

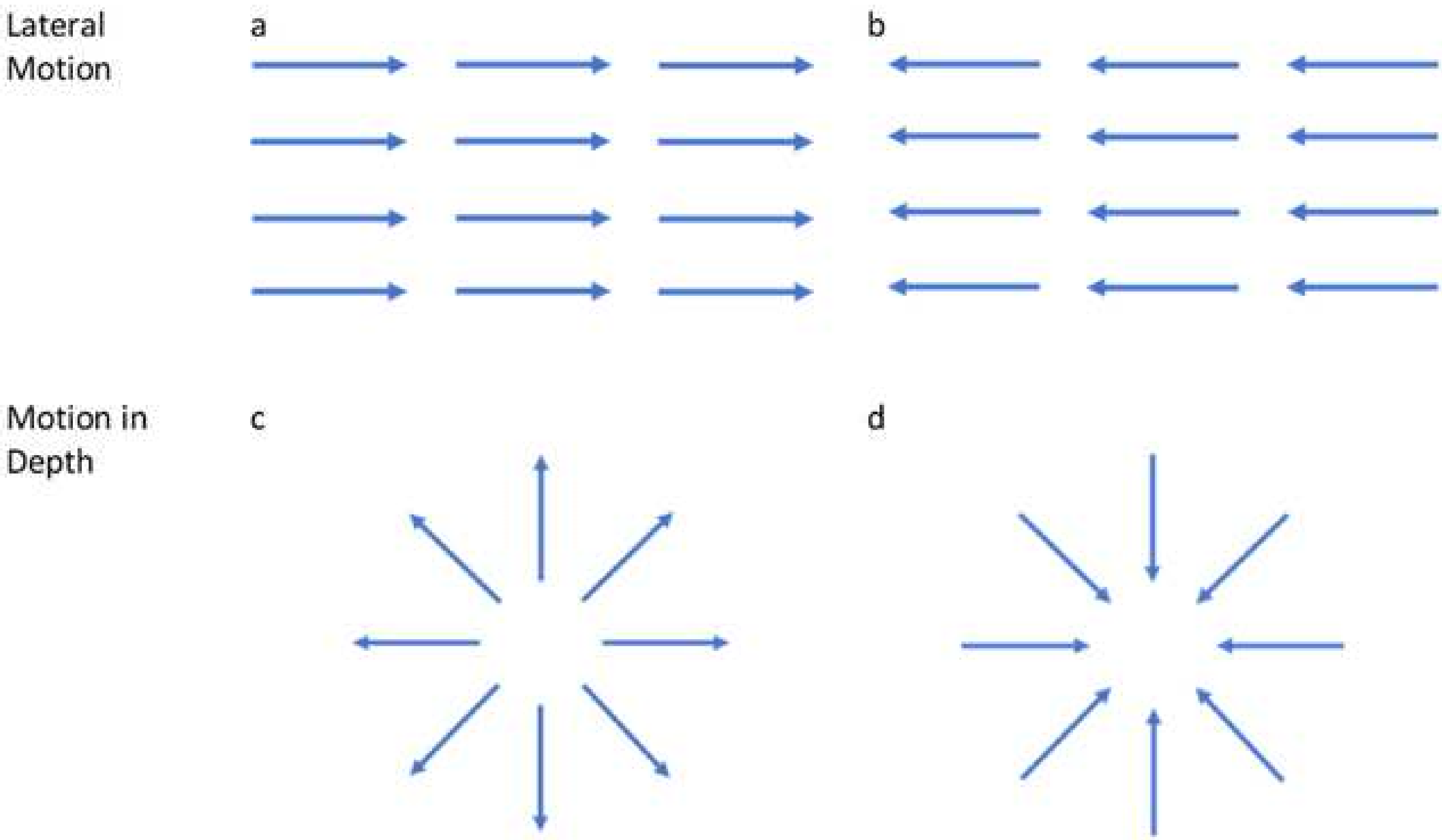
Lateral Motion
a
b
Motion in Depth
c
d

Figure 3

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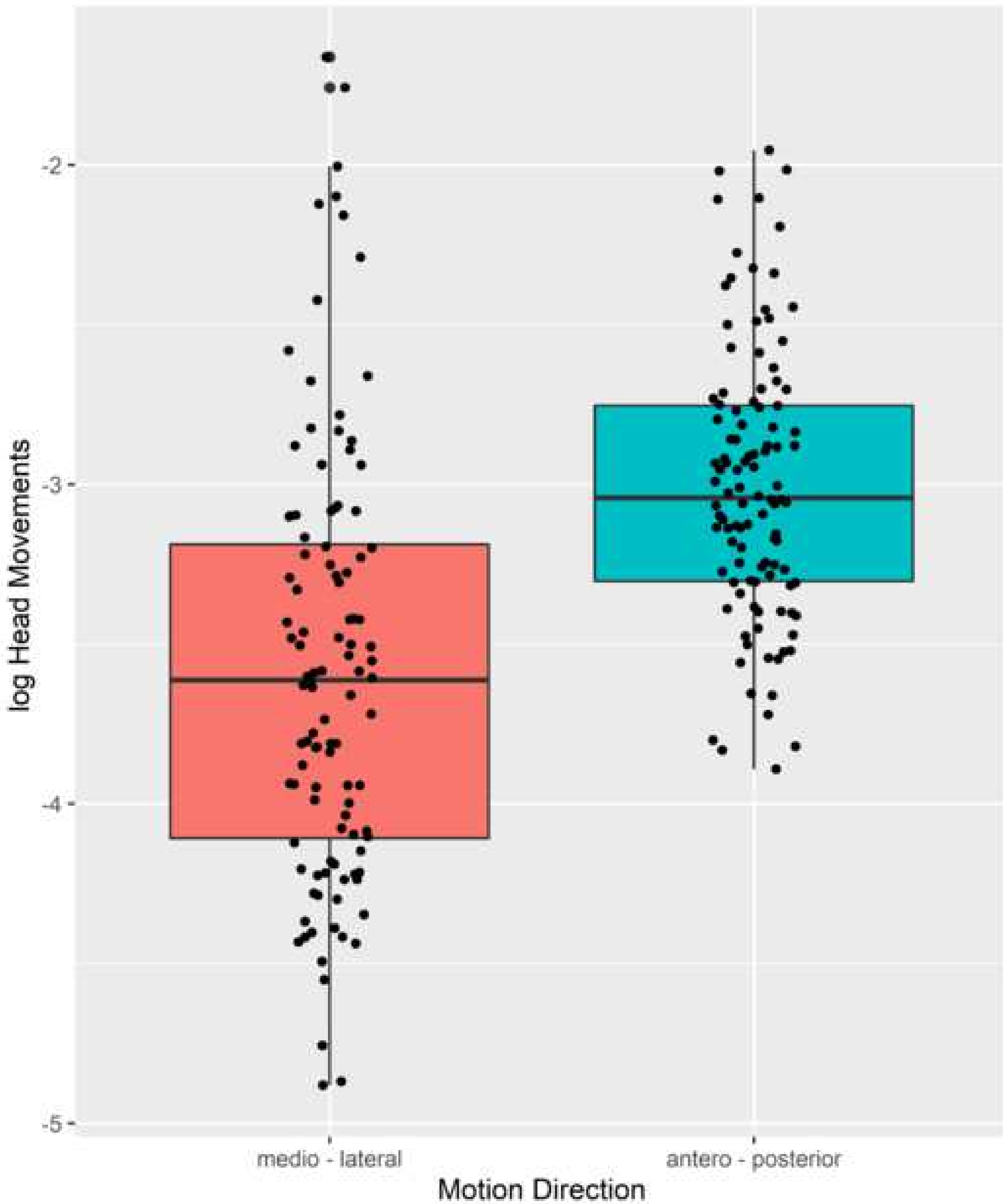
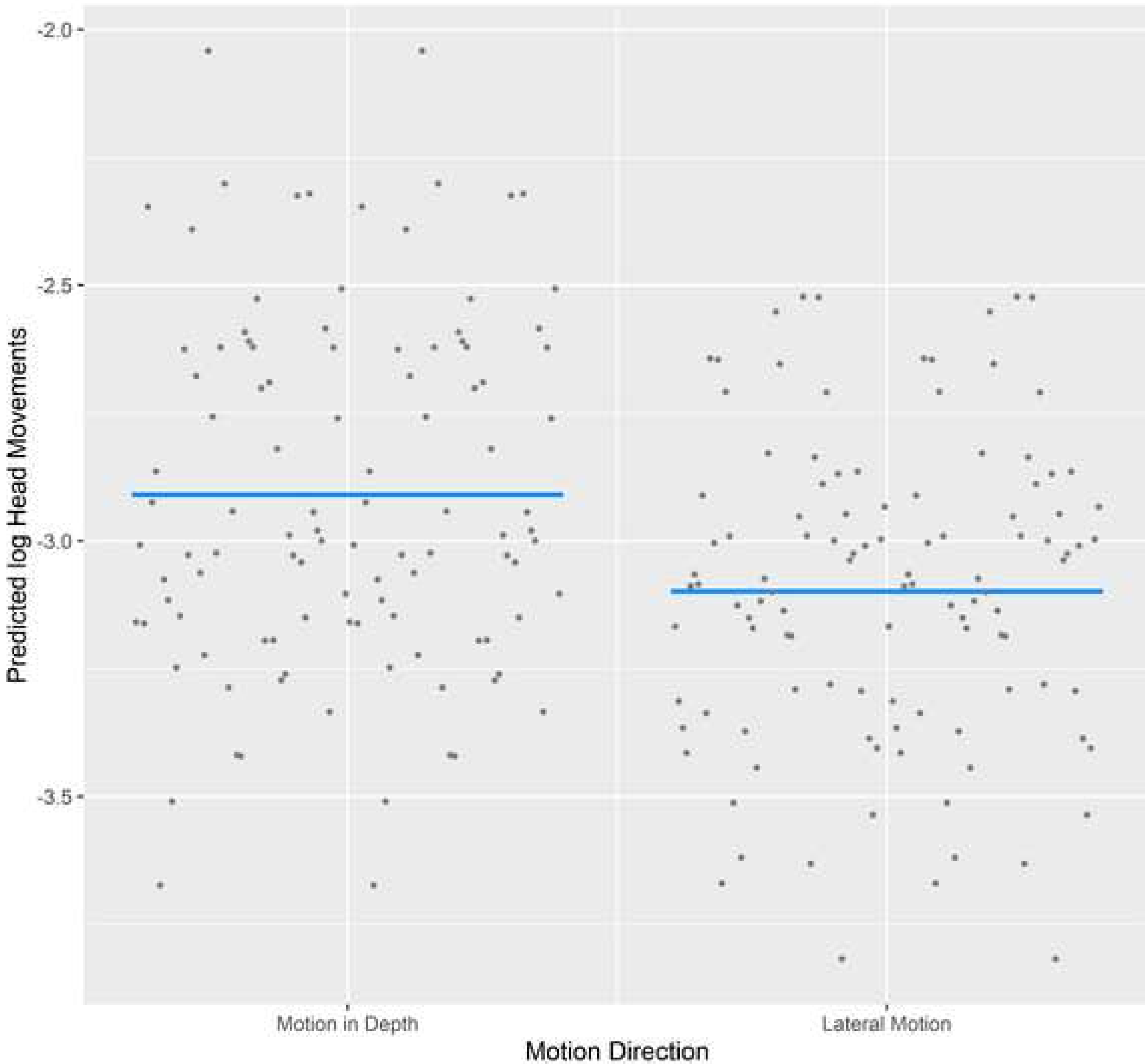


Figure 4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Predicted log Head Movements
Motion in Depth
Lateral Motion
Motion Direction

Figure 5

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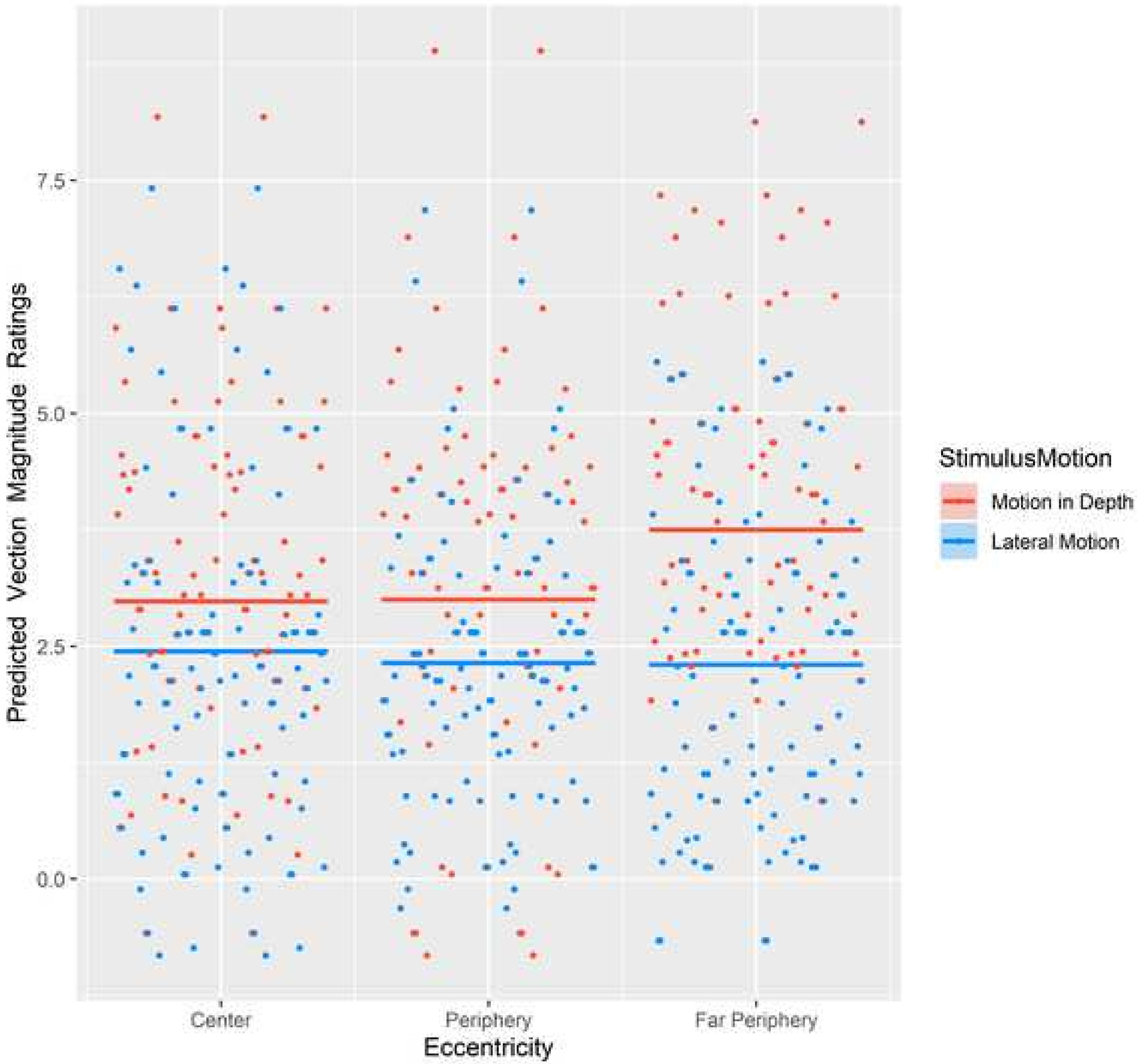

Figure6

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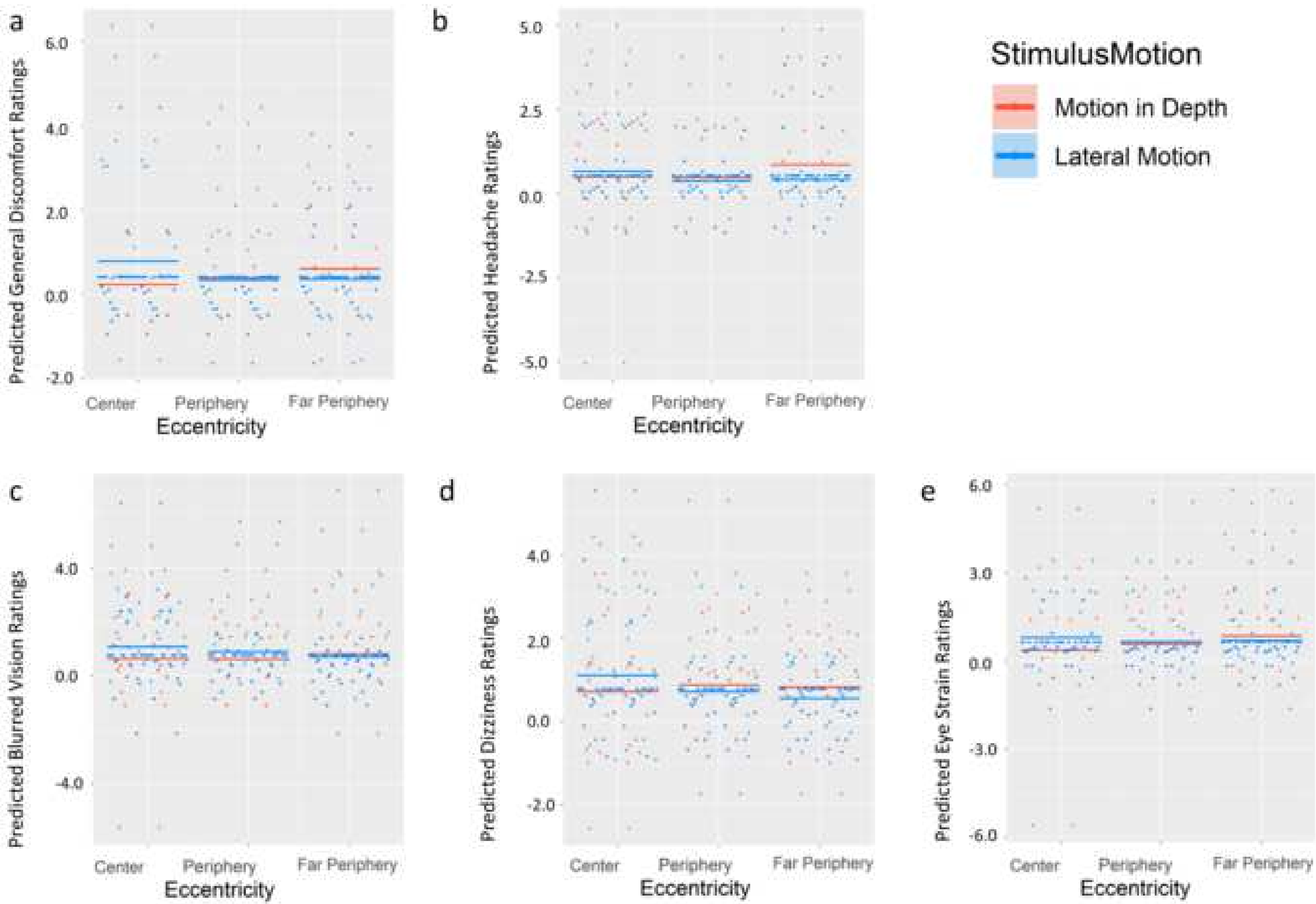
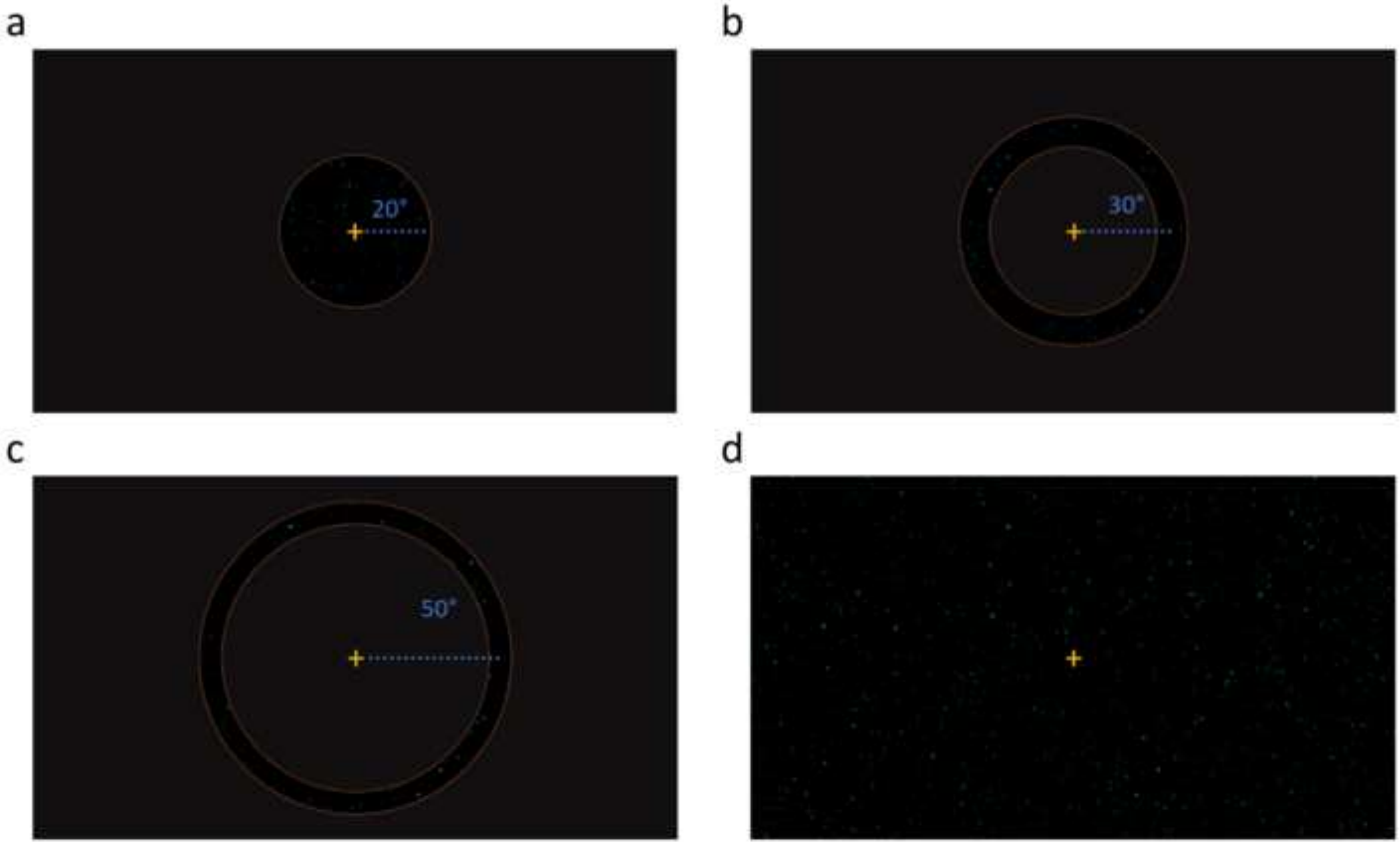


Figure 2



full FOV data

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