Displays

The Relationship between Vection, Cybersickness and Head Movements Elicited by Illusory Motion in Virtual Reality

--Manuscript Draft--

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Abstract:	Cybersickness is an unpleasant side effect of Virtual Reality and is often detrimental to a user's experience. It shows a complex relationship to vection (illusory self-motion) as well as postural instability. Three experiments were conducted presenting both expanding and rotating colourful optimised Fraser Wilcox illusions as well as grey-scaled controlled versions of the illusions. Cybersickness and vection were reported and head movements in medio-lateral and anterior-posterior direction were recorded. The experiments found that perceived visual motion (illusory motion) is sufficient to elicit vection in the absence of any stimulated visual motion. The strength of motion perceived in the illusions was related to the experience of cybersickness and vection, with illusions that were perceived as moving more eliciting stronger experiences of both. Surprisingly, rotating illusions were continuously perceived as moving more compared to expanding motion illusions, which could be related to missing stereoscopic motion-in-depth cues. Head movements were unrelated to any stimuli properties, suggesting that the motion signal elicited by the illusions might not have been strong enough to cause postural instability. Finally, dizziness has been identified as the possible link between cybersickness, vection and head movements supporting sensory conflict as well postural instability theories of cybersickness.
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To
Guangtao Zhai, PhD
Editor-in-chief, Displays

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7th September 2021

Dear Guangtao Zhai, PhD,

We would like to resubmit our manuscript entitled: "The Relationship between Vection, Cybersickness and Head Movements Elicited by Illusory Motion in Virtual Reality" as a research article to be published in *Displays*.
We think we have addressed all reviewers' comments in the manuscript in order to be considered for publication in Displays.

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

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Sincerely yours,

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

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

Reviewer 1

Point 1a: I will start with what I regard to be the least important of these two major issues first. In at least some of these experiments, observers were allowed to choose their optimal viewing distance for each stimulus - where the illusory motion in the static image was strongest. The greater the simulated viewing distance, the smaller the area of "motion stimulation". So, differences in these user-chosen settings resulted in images taking up somewhere between 4.3 degrees and 33.4 degrees in Experiment 1 and between 5.72 and 41.11 degrees in Experiment 2. While this might have been best for promoting the illusion of motion in the static image, it may not have been the best thing for the vection (as generally vection increases with the area of the visual motion stimulation; although I acknowledge that vection can be induced by small FOV stimuli). If I understand correctly illusion stimuli always covered the same area of the visual field in Experiment 3 (23 degrees). If so, the fact that the findings of Experiment 3 were similar to the other two experiments satisfies my concerns (but perhaps the authors could explicitly make this case for the readers). If not, then please see 1b.

Response Point 1a: *Thank you for this helpful comment. We have added an explanation to the general discussion for the reader. See page 43.*

"Observers were able to select their optimal viewing distance for the motion illusions presented in Experiment 2 resulting in the stimuli covering between 5.72° and 41.11° of the FOV. Vection strength generally increases with increasing stimulus size [54–56], therefore, changing the viewing distance and thereby the size of the motion illusions could have affected the experience of vection. In Experiment 3, however, viewing distance was held constant for all stimuli and all observers (23°) resulting in similar findings of illusion strength on vection and cybersickness as well as illusion type on illusion strength suggesting that the size of the perceived motion stimulus did not significantly affect the experience of vection."

Point 1b: The user-chosen settings for viewing distance should have introduced significant between-subjects and within-subjects variations in terms of their HMD users' vection experiences. I would see this as a big a problem when using a typical repeated measures ANOVA. I don't claim to have any particularly expertise in using linear mixed-method models (as are reported in this manuscript) - although I have read up on this for this review. If I understand correctly, the ability of LMM to look at random (as well as fixed) effects might well solve the problems arising from this decision. If they do, perhaps the authors could also address this directly in the manuscript.

Response 1b: *We have added a paragraph to the method section to clarify the advantages of linear mixed effect models in comparison to repeated measures ANOVAS. Explaining the random effects included in the models used for analysis. See page 12:*

“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 [71]. In the following experiments observer was included as a random effect in the models to account for variability in effects across observers. Stimulus was also included as a random effect in a first round of analyses was then, however, dropped as a random effect in the final models due to low variance in the random factor.”

Point 2: Throughout the manuscript the authors make many strong statements like: "illusion strength had NO EFFECT on head-movements in either the anterior-posterior or medio-lateral direction". However, they only conducted partial, and rather coarse, analyses of their participants' head-movements (since they were actually dealing with continuous 6 degrees of freedom HMD time series data). The reader is told that: "The maximum displacement[s] in both medio-lateral (x) and anterior-posterior direction[s] (z) with respect to stimulus and observer were calculated. Resulting in two displacement scores which served as a measure to estimate the head movements for each observer for each of the 14 stimuli in both medio-lateral and anterior-posterior direction." This at best provides a measure of the variability in x/z head position of the head-movement during each stimulus exposure (either 30 s or 90 s) [Note: it does not provide any information about changes in y position, yaw, pitch
or roll). However, let's not worry about that]. The biggest problem for me is that this analysis provides NO INFORMATION AT ALL about the TEMPORAL DYNAMICS of these user head-movements. If the authors were to perform a detrended fluctuation analysis (DFA) on these x and z position 1-D time series datasets, they might find significant differences in terms of DFA alpha. And there might (in turn) be significant relationships between these DFA alpha values and illusion strength/vection/discomfort/sickness. Alternatively, there might be no relationship between DFA alpha and illusion strength - which case these sorts of statements could remain in the manuscript. My point is that based on the information provided we cannot rule out the possibility that there are relationships involving head-movements and the key factors of interest. There are custom toolboxes in both Matlab and R that will run Detrended Fluctuation Analyses (they will take the 1-Dimensional x or z head
position data in as input, and then summarise that time series data into a single alpha output - (please see https://en.wikipedia.org/wiki/Detrended_fluctuation_analysis for interpretation). My guess is that if the authors do that, they will find that DFA alpha values are all greater than 1 (indicating the head-movement data is non-stationary). The question is then whether the DFA alpha values are significantly related to illusion strength, vection magnitude or cybersickness.

Alternatively, the authors could run Recurrence Quantification Analyses on these time series datasets (although these are trickier and more time consuming), or they could weaken/qualify these statements considerably. I strongly recommend the DFA in this situation - as it is likely the least amount of work. Apparently, time series data sets are better if they are longer than 60 s - however, the data for Experiments 2 and 3 were recorded for 90 s (which should make them ideal).

Response 2: *Thank you for bringing up this point. We agree that taking the maximum displacement for the two head movement direction does not take the temporal dynamics into account.*

We have performed a detrended fluctuation analysis for head movements in the x and z direction in all experiments and as the reviewer hypothesised DFA alpha values were greater than 1 or very close *to 1. We have included the relationship analyses for DFA alpha values and illusion type, illusion strength, cybersickness and vection in the supplementary materials.*

And have added the following paragraph to the analysis section for the first Experiment see page: 11:

"This analysis, however, does not take temporal dynamics into account, which is why a detrended fluctuation analysis (DFA) was performed on the head movements in all experiments resulting in DFA alpha values greater or very close to 1 indicating that head movement data is non-stationary. The relationship between the DFA alpha values and illusion strength, illusion type, cybersickness and vection magnitude can be found in the supplementary material 5 which is similar to the relationships found for maximum displacement of head movements."

We have also added the following paragraph to the general discussion to highlight the limitation of the current experiments in only investigate medio-lateral and anterior-posterior head movements and the need for research focusing on rotational head movements. See page 42:

"In the current experiments the magnitude of head movements was analysed for the medio-lateral and anterior-posterior directions only. Future research should additionally focus on the relationship between roll, yaw and pitch head movements and cybersickness as well as vection. A new theory of cybersickness focusing on the differences in virtual and physical head pose (DVP) has focused on the effects of these rotational head movements [96] highlighting the relationship between these head movements and cybersickness. Additionally, future research could focus on temporal dynamics of head movements and their relationship to adverse symptoms experienced in VR"

Supplementary analysis:

"Head movement analysis using detrended fluctuation analysis

Detrended fluctuation analysis (DFA) is often seen as the preferred method for the analysis of "scale free" data. For a review see for example (Bryce & Sprague, 2012; Hardstone et al., 2012; Poil, 2013). In the following the relationship between DFA alpha for head movements and illusion strength, illusion type, cybersickness and vection is described. DFA alpha is a self-similarity parameter it is the slope of the line in the range of time scales of interest and can be estimated using linear regression.

DFA was calculated using the DFA_fun function in Matlab (R2020b).

1. Experiment 1

1.1. Effect of Illusion type on Head movements

The scaling exponent alpha for head movements in medio – lateral and anterior – posterior directions were predicted using linear mixed effect models, including illusion type (rotating vs. expanding) as fixed effects and the intercept for observers as random effect. The function of the model for this and the following experiments looks as followed:

Model= lmer (αHead movements ~ Illusion Type+ (1|Observer))

No significant effect of illusion type was found for head movements in the medio – lateral direction ($F(1,376) = 1.14$, $p = .287$) or the anterior-posterior direction ($F(1,376) = 0.37$, $p = .542$).

1.2. Effect of illusion strength on Head movements

The scaling exponent alpha for head movements was predicted using a linear mixed effect model including illusion strength as fixed effect and intercept for observer as random effects. The function of the model looks as followed:

Model = lmer (αHead movements ~ Illusion Strength +(1|Observer))

No significant effect of illusion strength on medio - lateral head movements ($F(1, 329.07)= 1.20$, $p= .274$) or anterior-posterior head movements ($F(1, 299.69)= 0.59$, $p= .445$) was found.

1.3. Relationship between cybersickness and head movements

The scaling exponent alpha for head movements was predicted using a linear mixed effect model including general discomfort, headache, blurred vision, dizziness and eye strain as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiments looks as followed:

Model = lmer (αHead movements ~ General Discomfort + Headache + Blurred Vision +Dizziness+ Eye Strain + (1|Observer))

No significant effect of general discomfort ($F(1,373.17)= 0.05$, $p =.825$), headache ($F(1,351.97)= 0.08$, $p =.783$), blurred vision ($F(1,396.50)= 0.01$, $p =.918$), dizziness ($F(1,347.61)=0.39$, $p =.533$) or eye strain ratings ($F(1,317.04)= 0.39$, $p =.058$) on medio-lateral head movements was found. No significant effect of general discomfort ($F(1,360.45)= 0.25$, $p =.620$), headache ($F(1,334.46)= 1.59$, $p =.209$), blurred vision ($F(1,392.50)= 0.71$, $p =.399$), dizziness ($F(1,328.03)=0.19$, $p =.667$) or eye strain ratings ($F(1,296.14)= 0.003$, $p =.957$) on anterior-posterior head movements was found.

2. Experiment 2

2.1. Effect of illusion strength on Head movements

No significant effect of illusion strength on alpha for head movements in the medio-lateral ($F(1,254.52)= 0.51$, $p= .475$) or anterior-posterior direction ($F(1,251.71)= 0.58$, $p= .445$) was found.

2.2. Relationship between cybersickness and head movements

A significant effect of general discomfort ($F(1, 238.10)= 4.74$, $p =.030$, $f2 = .02$, $\Delta BIC = -0.81$) and headache ($F(1, 204.74)= 7.04$, $p =.009$, $f2 = .03$, $\Delta BIC = 1.60$) on alpha for head movements in the medio-lateral direction was found. DFA alpha increased by 0.02 for each increase in general discomfort rating and decreased by 0.03 for each increase in headache rating. No significant effect of blurred vision ($F(1,172.58)= 0.02$, $p =.895$), dizziness ($F(1,179.04)= 1.78$, $p =.183$), or eye strain ($F(1,229.23)= 0.10$, $p =.758$) on alpha for medio-lateral head movements was found.

No significant effect of general discomfort (F(1,231.05)= 0.20, p =.656), headache (F(1,192.69)= 2.50, p =.116), blurred vision (F(1,158.32)= 0.41, p =.52), dizziness (F(1,165.06)= 1.02, p =.0.31), or eye strain (F(1,220.17)= 0.13, p =.722) on alpha for anterior-posterior head movements was found.

2.3. Relationship between vection measures and head movements

The scaling exponent alpha for head movements was predicted using a linear mixed effect model including vection magnitude and vection onset as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiment looks as followed:

Model = lmer (αHead movements ⍰ Vection Magnitude + Vection Onset + (1|Observer))

No significant effect of vection magnitude (F(1,118.32)= 0.28, p =.597) or vection onset (F(1,147.84)= 0.01, p =.920) on alpha for medio-lateral head movements was found. Similarly, no significant effect of vection magnitude (F(1,138.21)= 2.70, p =.103) or vection onset times(F(1, 155.65)= 0.60, p =.440) was found on alpha for anterior-posterior head movements.

3. Experiment 3

3.1. Effect of Illusion type on Head movements

No significant effect of illusion type was found for alpha for head movements in the medio – lateral direction (F(1,580.93) = 0.0001, p = .991) or the anterior-posterior direction (F(1,581.08) = 0.05, p = .831).

3.2. Effect of illusion strength on Head movements

No significant effect of illusion strength on alpha for head movements in the medio-lateral (F(1,629.67)= 0.10, p= .757) or anterior-posterior direction (F(1,625.72)= 0.67, p= .413) was found.

3.3. Relationship between cybersickness and head movements

No significant effect of general discomfort (F(1,621.62)= 0.07, p =.792), headache (F(1,627.46)= 0.79, p =.374), blurred vision (F(1,566.41)= 0.39, p =.533), dizziness (F(1,626.86)= 0.63, p =.429), or eye strain (F(1,586.66)= 0.26, p =.429) on alpha for medio-lateral head movements was found. Similarly, no significant effect of general discomfort (F(1,540.97)= 0.58, p =.448), headache (F(1,616.21)= 0.04, p =.835), blurred vision (F(1,418.80)= 0.11, p =.746), dizziness (F(1,570.02)= 0.26, p =.608), or eye strain (F(1,463.50)= 0.50, p =.482) on anterior-posterior head movements was found.

3.4. Relationship between vection measures and head movements

No significant effect of vection magnitude (F(1,342.76)= 0.17, p =.679) or vection onset (F(1,344.85)= 0.44, p =.506) or vection duration times (F(1,145.20)= 1,14, p =.286) on alpha for medio-lateral head movements was found. Similarly, no significant effect of vection magnitude (F(1,286.06)= 0.04, p =.838) or vection onset times(F(1,296.76)= 0.02, p =.887) or vection duration"

Point 3: Page 9: "Nine of them identifying as male and 21 as female ranging in age from18 to 39 years". While I appreciate the sensitivity of this - if one truly believes that there are differences between genders in susceptibility to cybersickness (and I am not sure about this), they would likely to be due to biology (rather than gender identification). So, I think statements like this will probably hinder attempts at replication these reported biological sex effects.

Response 3: *We agree with the reviewer that "gender differences" in cybersickness (if they exist) will be based on differences in biological sex rather than gender identity. We have therefore removed gender information from the manuscript to prevent confusion.*

Point 4: Page 9 "completely covers the field of view". Not really in the Oculus Rift - which is one reason the Valve index was used to stimulate a greater area of the visual field.

Response 4: *We have rephrased this:*

"This headset covers 90° of the FOV of the user and completely occludes the rest of their surroundings."

Point 5: Page 12: Participants had 10-15 minutes of VR gameplay prior to the actual experiment. I have played this first-person POV Spiderman: Homecoming game. I am surprised that no participants dropped out at all. Was sickness severity assessed both before and after this HMD VR game? I don't really see why this was necessary or useful. I would be concerned that it might have at least increased their susceptibility to cybersickness with the Fraser-Wilcox stimuli. It might have also altered their likelihood of experiencing vection. Perhaps try to justify this a bit more strongly.

Response 5: *Sickness severity in the current experiments was not assessed prior to or directly after the game. We agree with the reviewer's comment. In hindsight a sickness measures such as the SSQ should have been provide before and after the game to directly measure its effect on the participants level of cybersickness.*

We can not rule out that the game might have affected the overall experience of cybersickness in participants and might have altered their likelihood of experiencing vection, but we believe that the measure of cybersickness used in the current study after each motion illusion stimulus was still able to pick up differences in experienced cybersickness caused by the illusions. The experience of cybersickness was strongly affected by perceived illusion strength in all experiments, with illusions that were perceived as moving more also eliciting a stronger sensation of cybersickness. Similarly, illusions that were perceived as moving more also elicited a stronger sensation of vection suggesting that even if the game affected participants susceptibility to vection and cybersickness the perceived motion in the illusions still affected both vection and cybersickness.

As most of our participants had never used a VR headset prior to the experiment we felt it was necessary to give them a chance to familiarise themselves with the headset, the virtual environment as well as the controllers prior to the experiment.

We have added a paragraph to the general discussion:

"Allowing observers to play a first-person Spiderman game prior to the experiment could have affected their susceptibility to cybersickness and vection for the following motion illusions. In future research cybersickness severity should be assessed before and after such introductory VR games to directly measure their effects on observers cybersickness levels. However, this gameplay took place before the experiment for all observers, and any affect on the later experience of vection would have affected all stimuli. The experience of cybersickness was strongly affected by perceived illusion strength in all experiments, with illusions that were perceived as moving more also eliciting a

stronger sensation of cybersickness. Similarly, illusions that were perceived as moving more also elicited a stronger sensation of vection."

Point 6: Page 14: "ration test" Suspect this should be "ratio test"

Response 6: *Thank you for pointing this out to us. It has been changed to "ratio test"*

Point 7: Page 14: "As an additional effect measures Cohen's f2 was calculated for fixed effects showing a significant effect using the "r.squaredGLMM" of the MuMIn package [76] to calculate R2 for the full an null model allowing to determine the Cohen's f2 of the fixed effects using the following function:" This sentence should probably be rephrased - it is very hard to parse/follow.

Response 7: *We have rephrased the sentence:*

"As an additional measure of effect size Cohen's f2 was calculated for fixed effects showing a significant effect using the "r.squaredGLMM" of the MuMIn package [77]. R2 for the full an null model were calculated and used to determine Cohen's f2 of the fixed effects:"

Point 8: Page 18: Having the results for Experiments 1, 2 and 3 - before we know what is being examined in Experiments 2 and 3 - is a little strange. Perhaps consider including each plot in their own experiment sections.

Response 8: *We have included a separate plot for each experiment section.*

Point 9: Page 21: "Vection is believed to cause postural instability". The relationship between vection and postural sway is a complex one. Vection can both increase postural sway and postural instability. However, visual motion stimulation (in the absence of vection) can also do both these things. Some researchers have argued that there are two types of postural control mechanisms: 1) automatic responses based on preconscious processing of visual motion; and 2) vection/conscious responses (which start later on when exposed to global optic flow). So, I would recommend qualifying this statement to capture these different possibilities.

Response 9: *We have added the following paragraph to the manuscript:*

"However, postural instability can also be affected by visual motion stimulation independent of vection. Postural control mechanisms are believed to be based on both automatic preconscious processing of visual motion as well as the conscious processing of an optic flow stimulus. Postural sway caused purely by visual motion is preconscious whereas postural sway caused by vection is a more conscious process [86,87]. Postural sway caused by visual motion itself will be represented in the relationship between head movements and illusion strength ratings and postural sway caused by vection will be represented in the relationship between vection magnitude ratings and head movements."

Point 10: Page 21: "Forty-five observers" - had any of these observers previously participated in Experiment 1 or were they all naïve?

Response 10: *We mention in the general discussion that: "Eleven of the observers participated in 2 of the three experiments (three observers participated in Experiment 1 and 2, three in Experiment 2 and*

3 and five in Experiment 1 and 3), with none of the observers taking part in all three experiments and the rest of the observers only participating in one experiment, again indicating robust findings.

Point 11: Page 23: "with more head movements in the anterior-posterior … direction" I am surprised there was not more head-movement change in the medio-lateral direction for the rotational stimuli - which seemed to be producing roll motion/vection. This might be better captured in the head-orientation (rather than the head-position) data (which admittedly is a bit difficult to calculate). I am curious whether anything interesting emerges when you look at the temporal dynamics of the x or z head position data.

Response 11: *Thank you again for bringing up this point. We have added the following paragraph to the general discussion, see page 42:*

"Based on rotating motion illusions being perceived as moving more and eliciting a stronger sensation of vection, however, more head movements in the medio-lateral direction would have been expected. Roll vection could potentially affect head-orientation rather than head movements which could explain these results."

Point 12: Page 24: "vection magnitude and vection onset as fixed effect". I think this should be "fixed effects".

Response 12: *Thank you for pointing this out. We have changed it to "fixed effects".*

Point 13: Page 25: "No significant effect of general discomfort ($F(1,241.36)= 1.14$, $p =.286$), headache ($F(1,250.14)= 1.70$, $p =.193$), blurred vision ($F(1,251.99)= 1.31$, $p =.253$), dizziness ($F(1,251.91)= 0.11$, $p =.742$), or eye strain ($F(1,244.29)= 1.07$, $p =.303$) on medio-lateral head movements was found. Similarly, no significant effect of general discomfort ($F(1,248.26)= 0.22$, $p =.637$), headache ($F(1,251.72)= 0.15$, $p =.698$), blurred vision ($F(1,247.13)= 0.44$, $p =.508$), dizziness ($F(1,248.27)= 0.04$, $p =.839$), or eye strain ($F(1,250.39)= 0.51$, $p =.478$) on anterior-posterior head movements was found." And page 26: "No significant effect of vection magnitude ($F(1,156.56)= 2.22$, $p =.139$) or vection onset ($F(1,152.2)= 0.19$, $p =.660$) on medio-lateral head movements was found. Similarly, no significant effect of vection magnitude ($F(1,157.78)= 0.13$, $p =.721$) or vection onset times($F(1,154.43)= 0.24$, $p =.627$) was found on anterior-posterior head movements."
These are just two examples - yes I agree no significant relationships were found for positional variability. But what about in terms of the temporal dynamics of these movements (how head movements changed over the 30 or 90 second exposures)?

Response 13: *We have also added the following paragraph to the general discussion to highlight the limitation of the current experiments in only investigate medio-lateral and anterior-posterior head movements and the need for research focusing on rotational head movements. See page 42.*

"In the current experiments the magnitude of head movements was analysed for the medio-lateral and anterior-posterior directions only. Future research should additionally focus on the relationship between roll, yaw and pitch head movements and cybersickness as well as vection. A new theory of cybersickness focusing on the differences in virtual and physical head pose (DVP) has focused on the effects of these rotational head movements [96] highlighting the relationship between these head movements and cybersickness. Additionally, future research could focus on temporal dynamics of head movements and their relationship to adverse symptoms experienced in VR"

And have included the DVP analysis in the supplementary materials, see Point 2.

Point 14: Page 26 "There was no relationship between either discomfort or vection and head movements." This is a little confusing - I would suggest rephrasing it. There is no relationship between discomfort and head-movements. There was also no relationship between vection magnitude and head-movements (although in both cases head-movements only refers to positional variability - we are currently not sure whether there might be relationships with other types of head-movement measures).

Response 14: *We have rephrased this sentence:*

"There is no relationship between discomfort and head-movements. There was also no relationship between vection magnitude and head-movements (although in both cases head-movements only refers to positional variability)."

Reviewer 2

Point 1: There are discrepancies between the motivation of the investigation and the experiments actually executed. The authors insisted that they employed the visual illusion as a vection/motion sickness inducer in order to avoid a side effect of accommodation or vergence. However, they can also avoid the effects of accommodation/vergence with using a physically moving visual stimulus on the observer's front-parallel plane without binocular information (not only a rotational motion but also an expansion). Furthermore, they did not actually measure the observer's accommodation/vergence. It would be possible that perceptual modulation of the stimulus depth might affect the observer's accommodation (e.g., Takeda et al, 1999 Vision Research). Thus, main motivation of this series of experiments should be whether vection and cybersickness would be caused by the illusory motion which contained no physical motion energy.

Response 1: *Based on the recommendation of the reviewer we have changed the main motivation of the current paper. We have added the following to the introduction, see page 4:*

"Research suggest that the experience of vection does not require explicit motion, as perceived stimulus motion can also elicit vection in the absence of any physical stimulus motion [20,32,33]. The current experiments aim to add to the existing research by investigate whether illusory motion, which does not contain any physical motion energy, can cause vection as well as cybersickness. We used optimised Fraser Wilcox illusions in the following experiments, as they elicit apparent motion from a stationary image [34]."

Point 2: In Experiments 1 and 2, the sizes of the visual stimuli were individually set to optimal for each observer to elicit stronger motion illusion. The sizes ranged from 4.3 to 33.4 degree in experiment 1, and from 5.72 to 41.11 degree in experiment 2. The size of the visual inducer would be a primary factor in vection and motion sickness induction. Vection and motion sickness (and also head movement) would not be comparable between the smaller and the bigger stimulus conditions with such an extreme separation. Indeed, visual inducer with a size of 5.72 degree (the smallest one in experiment 2) seemed not be able to effectively induce self-motion perception (because it was so small). The present investigation revealed positive correlation between vection and cybersickness, but I guessed it would be due to the situation where the smaller display yielded weaker (or no) self-motion perception and motion sickness and the bigger display caused stronger vection and motion sickness (it is not so surprising). Physically controlled stimulus size would be very important in examining visually induced self-motion perception and motion sickness.

Response 2: Reviewer 1 brought up the same point. *See Reviewer 1 Point 1a: We have added an explanation to the general discussion for the reader. See page 43.*

"Observers were able to select their optimal viewing distance for the motion illusions presented in Experiment 2 resulting in the stimuli covering between 5.72° and 41.11° of the FOV. Vection strength generally increases with increasing stimulus size [54–56], therefore, changing the viewing distance and thereby the size of the motion illusions could have affected the experience of vection. In Experiment 3, however, viewing distance was held constant for all stimuli and all observers (23°) resulting in similar findings of illusion strength on vection and cybersickness as well as illusion type on illusion strength suggesting that the size of the perceived motion stimulus did not significantly affect the experience of vection."

We agree with the reviewer that stimuli in Experiment 1 and 2 were not well controlled. This was the reason for Experiment 3 in which the size of the presented motion illusions as well as their colour were kept constant.

Point 3: In some conditions, the visual stimulus was composed of multiple parts of visual illusion each of which can independently induce illusory rotation or expansion as indicated in figures 1 and 8. Vection is induced by the global and uniform motion of the visual inducer. Previous study indicated that local rotation of the visual inducer was ignored and irrelevant to vection induction (Nakamura, 2015 Frontiers in Psychology). It should be difficult to assume that the observers perceived actual self-motion with the visual inducer with multiple centers of rotation or focuses of expansion. If it would be a case, how axis of self-rotation and direction of forward self-motion would be? It is well known that vection is highly affected by the observer's cognitive bias (e.g., Lepecq et al, 1995 Perception). I'm afraid that vection measured in the current experiments would reflect demand characteristic, not real percept.

Response 3: *Thank you for bringing Nakamura's paper (2015) to our attention. Nakamura states in his study that:*

" The results of the two psychophysical experiments revealed that roll vection became stronger in the condition where the rotations of the visual elements" (local rotation) "were consistent with the global rotation of the visual stimulus."

He also states that:

"In the conditions where the visual elements rotated inconsistently with the global pattern rotation (none, same, and opposite directions and random local rotations), vection strengths were decreased"

And:

"perceptual process responsible for perception and control of self-motion can not be determined merely by the output of the global motion detector […]. The local motion signal is clearly not negligible in vection even if it is irrelevant to global motion integration."

We have included a paragraph in the introduction to make the reader aware that the local motion is perceived in the Fraser Wilcox illusions. See page 5:

"Vection research so far has mainly focused on global motion stimuli, however, local rotation has been shown to be able to affect roll vection elicited by a global rotation stimulus [41]. Locally rotating elements can enhance and inhibit the experience of vection depending on their congruency with the global motion stimulus [41]. The illusions in the current experiments are composed of multiple parts of visual illusion each of which can independently induce illusory rotation or expansion. Based on Nakamura's work we hypothesised that these local motion signals would be able to elicit a sensation of vection even though weaker than if elicited by a global motion stimulus."

We have also included a paragraph in the discussion addressing observers' possible cognitive biases towards their experience of vection. See page 40:

"It has been shown that the experience of vection can be highly affected by an observer's cognitive bias [99-101]. Therefore, informing observers prior to the experience that the presented stimuli could induce vection might have biased their perception of vection in the current experiments. If this was the case the reported vection in the current experiments would reflect demand characteristics rather than a real perception of vection. However, if cognitive bias alone is responsible for the experience of vection we would expect all illusions to elicit a similar sensation of vection independent of the strength of illusory motion perceived in them. In all experiments reported here vection magnitude was strongly affected by illusion strength, which would suggest that vection in the current study is at least partially affected by the motion perceived in the illusions. Additionally, if the experience of vection was solely due to demand characteristics the responses in the 2AFC pilot (see Supplementary Material 4) should have worked out at chance with all illusions being picked as the "stronger one" in around half of the trials. However, the findings showed a clear dominance of rotating illusions as well as an effect of spatial frequency on the response choices. Some observers also did not experience any vection for some motion illusions. In Experiment 2 no vection was experienced in 31 out of 258 presentations and in Experiment 3 no vection at all was experienced for 367 out of 912 presentations. The explanation of vection and instruction for the task were also the same for each observer, if vection was solely caused by biases and demand characteristics, each observer would have been expected to experience vection for the motion illusions. However, one of the 45 observers in Experiment 2 and seven of the 71 observers in Experiment 3 experienced no vection."

Point 4: One of the serious drawbacks of experiments is lack of control condition. The visual stimulus appeared to be similar as Fraser-Wilcox illusion but which cannot elicit illusory motion can be easily created with a manipulation of contrast of stimulus components. If such a stimulus is employed as a control stimulus, one can differentiate whether vection, cybersickness and head motion confirmed in experiments were caused by the illusory motion perception or not. It would be possible that this kind of visual stimulus might evoke head motion or symptom of nausea even without illusory motion especially in a case using HMD.

Response 4: *Thank you for bringing up this point. We agree with the reviewer that a control condition could have added to the research. it could be that part of the cybersickness and vection experienced is unrelated to the illusory motion perceived in the illusions. However, due to the relationship found between illusion strength and discomfort as well as vection magnitude we believe that the motion perceived from the illusions is at least partially responsible for the experience of vection and cybersickness. Based on your comment we have added the following paragraph the the discussion. See page 41:*

"The current experiments did not include a control condition. It is possible to manipulate the colour pattern in a way so that illusory motion is much reduced, for example see [63]. By using such a control condition is would be possible to gauge whether experienced cybersickness, vection and head movements are caused by the perceived motion in the illusion or another effect, such as the gameplay at the beginning, or the virtual environment in general. . However, due to the relationship found between illusion strength and cybersickness as well as vection magnitude we believe that the motion perceived from the illusions is at least partially responsible for the experience of vection and cybersickness. Further research into the effects of Fraser Wilcox illusions on cybersickness, vection and head movements, however, should include a control condition to give more insight into the effects of perceived motion."

Point 5: In introduction, the authors enhanced a significance of employing HMD as a stimulus-presentation apparatus in experiments which intended to examine vection and cybersickness. On the other hand, there were no discussions concerning differences between HMD and the other visual displays (e.g., LCD flat display or screen projector). One of the remarkable features of HMD would be that observer's head motion is feedbacked to a visual display. If the visual feedback was not implemented in the experiments reported here, what was a substantial difference between HMD and the other displays? The authors described that time lag between the head motion and visual feedback can be a potential factor of cybersickness. But, they must discuss it based on the results of the experiments.

Response 5: *We agree with the reviewer that the lag between head motion and visual feedback as a potential factor of cybersickness (DVP theory) does not fully relate to the current experiment, as lag would have been the same for all conditions. We have therefore removed the paragraph from the discussion. The headsets used in the current experiments are standard commercial headsets and do feedback the head motion to the visual display.*

We have included the following paragraph in the introduction to highlight the differences between VR headsets and other visual display types, see page 3:

"This complete occlusion of the real world is one of the main differences between HMDs and other visual displays (e.g. LCD, flat displays or screen projectors). Additionally, some advantages of HMDs compared to desktop displays have been discussed, such as their wider FOV, they allow for stereoscopic presentation, for more movement in the user and they allow for a complete occlusion of the surrounding environment, which can increase immersion and presence, which in turn has beneficial effects on treatment and training outcomes as well as game enjoyment [17,18]."

Point 6: Attributes of each visual stimulus employed in each stimulus should be described in more detail with physical dimensions. On bottom of page24, the authors wrote that spatial frequency of the visual stimulus affected strength of the visual illusion (if so, vection and cybersickness also affected by the spatial frequency of the visual stimulus). On the other hand, there were no correspondent description of the effects of the spatial frequency in the result sections of experiments 1 and 2. If there were any differences caused by the physical differences of the visual stimuli, it should be clearly described and discussed.

Response 6: *We have added the analysis for the effect of spatial frequency on illusion strength, cybersickness ratings and vection for Experiment 1 and 2 as Supplementary materials 4.*

Additionally, we have added the following paragraph to the discussion of Experiment 2:

"Spatial frequency of the stimuli has been shown to affect illusion strength ratings in Experiment 1 and 2 as well as some of the cybersickness measures (Experiment 1: eye strain; Experiment 2: general discomfort, dizziness and eye strain) as well as vection magnitude and vection onset times (see Supplementary Material 4), with low spatial frequency stimuli in general being perceived as moving more, causing more discomfort and vection."

Point 7: What the abscissa of the scatter plots indicated (figures 3 and 9)? If it only reflected the difference of the observation, and then, contained no particular meanings, averages and deviations of the predicted would be sufficient? The results of the simulation based on the linear model were summarized in tables, but descriptions about them in the main text were not exhaustive. Including the case of non-significant effect, the results of the simulation should also be described in the text.

Response 7: *The two figures (now figure 3 and 10) represent the residuals of the model prediction shown using the visreg function in R, rather than simple scatterplots. The x-axis reflects the difference in the two observations. For figure 3 it represents the two motion directions (medio-lateral and anterior-posterior direction) and for figure 10 it represents the two illusion types (expanding and rotating). The singular points represent residuals, and the lines represent model fits. See:*

"Experiment 1: Predicted head movements in medio-lateral and anterior-posterior direction. 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.

Experiment 3: Predicted vection magnitude ratings for expanding and rotating motion illusions. 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."

Visreg has been suggested as a tool to visualise regression models in general and specifically linear mixed effect models as used in the current experiments.

See:

Breheny, P., & Burchett, W. (2017). Visualization of regression models using visreg. R J., 9(2), 56.

chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=http%3A%2F%2F

www.hiercourse.com%2Fdocs%2FRnotes_mixed.pdf&clen=1571796&chunk=true

We have added a description of results to the main text for all results reported in the tables. See pages 14, 17, 25, 30 and 34.

"Observers experienced significantly more general discomfort and blurred vision for rotating illusions compared to expanding illusions. However, no differences in headache, dizziness or eye strain ratings were found for the illusion types."

"General discomfort, dizziness and eye strain ratings increased significantly with increasing illusion strength, whereas blurred vision and headache ratings were not significantly affected by illusion strength."

"Vection magnitude ratings significantly affected all the cybersickness measures, with illusions eliciting a stronger sensation of vection also leading to a stronger sensation of adverse symptoms. Vection onset times only significantly affected blurred vision ratings, with shorter vection onset times being experienced for stimuli eliciting a stronger sensation of blurred vision."

"Observers experienced significantly more eye strain for rotating compared to expanding illusions. None of the other cybersickness measures differed significantly between the two illusion types."

"Vection magnitude showed a significant relationship with general discomfort, blurred vision, dizziness and eyestrain. However, no significant relationship between vection magnitude and headache ratings was found. No relationship between cybersickness measures and vection onset or duration times were found."

Point 8: I don't know whether it is due to the author, I cannot find supplemental materials on the web system.

Response 8: *Supplementary materials had been added to the system. Hopefully the editor will be able to direct you to them.*

Highlights:

- Perceived visual motion is sufficient to elicit vection in the absence of stimulated visual motion
- Illusory motion perceived in optimised Fraser Wilcox illusion related to cybersickness and vection
- Rotating motion illusions are perceived as moving more compared to identical expanding motion illusions
- Dizziness could be the possible link between cybersickness symptoms, vection and postural instability experienced in VR

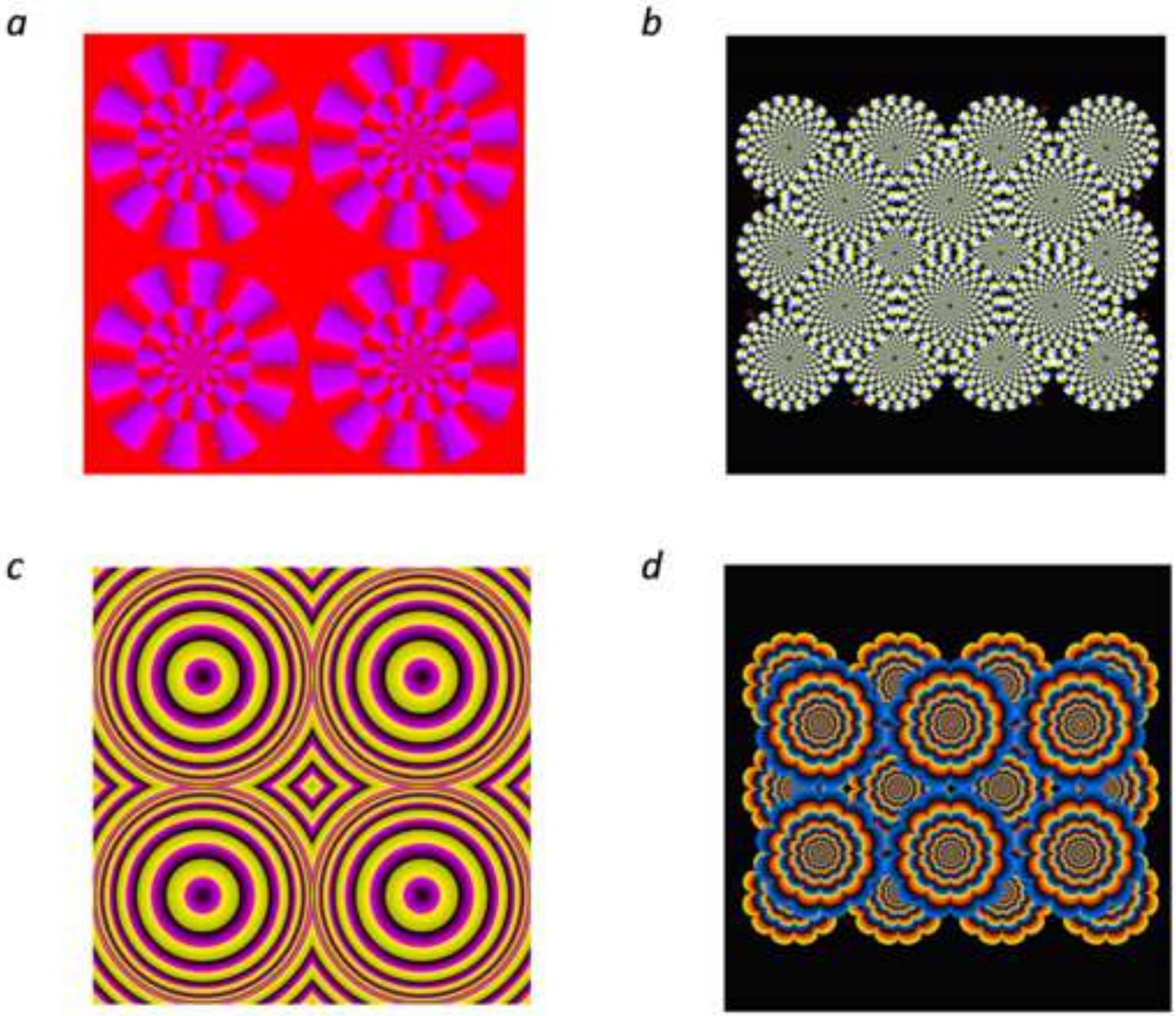


Figure 2

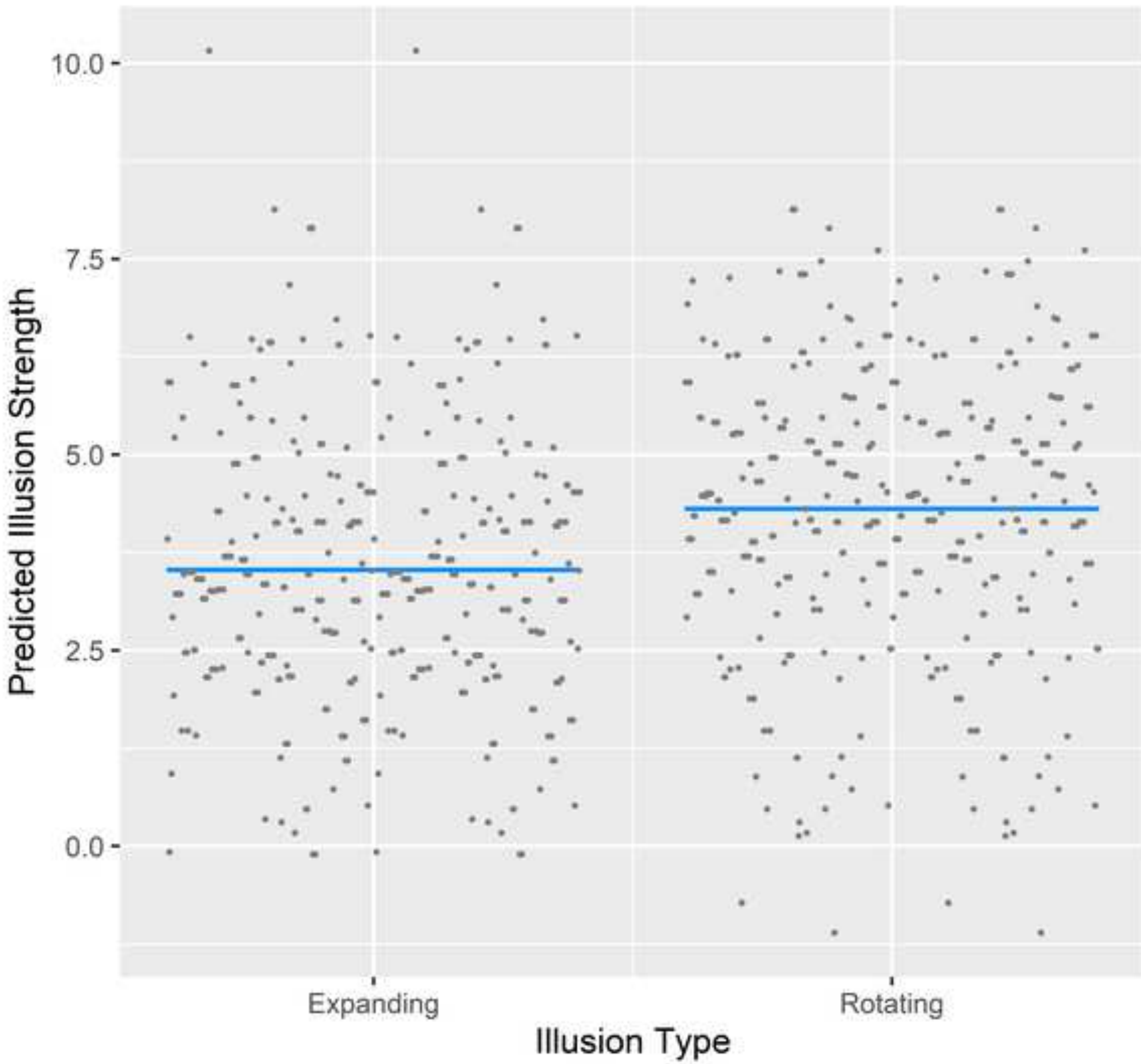
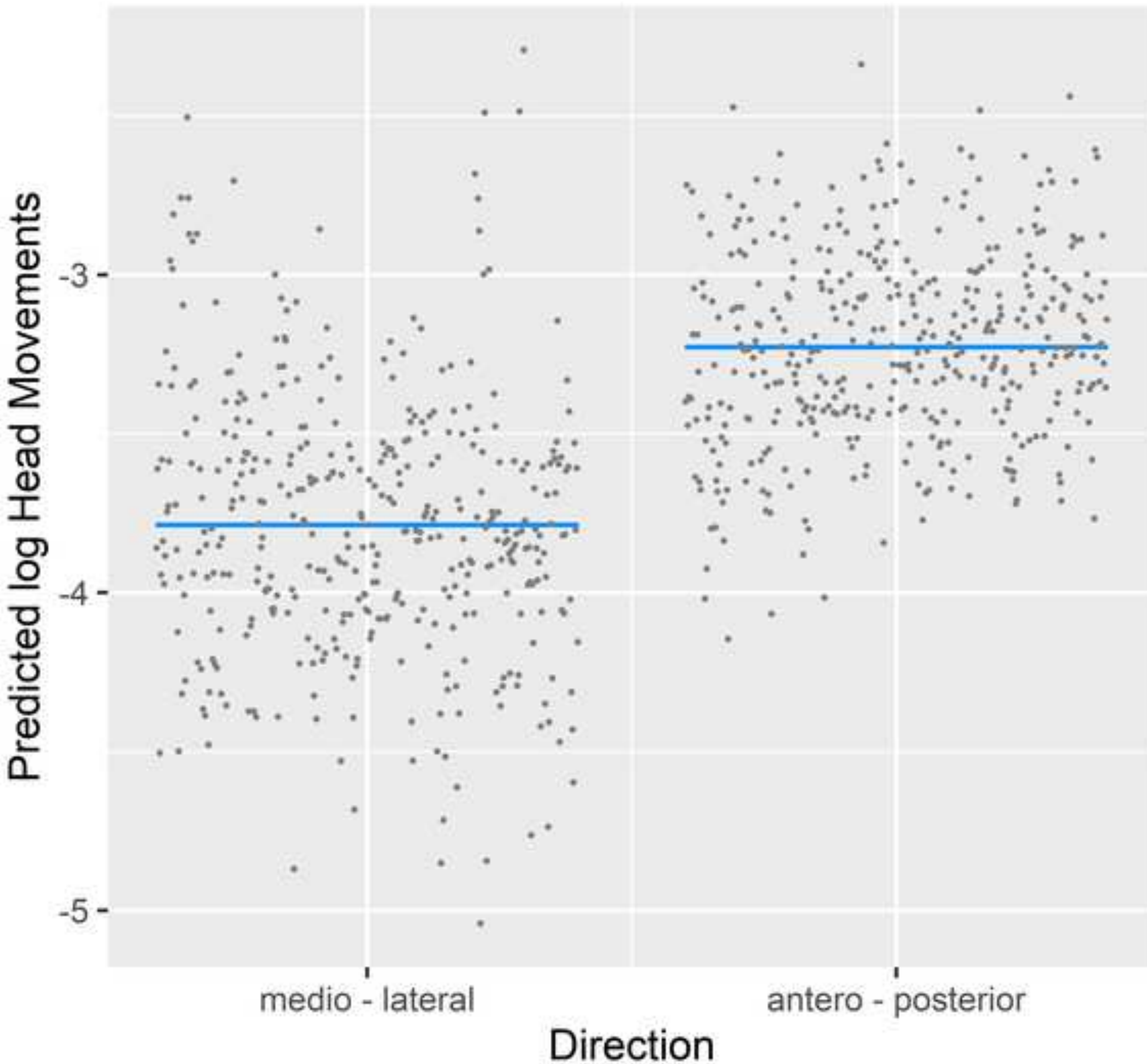

10.0
7.5
5.0
2.5
0.0
Predicted Illusion Strength
Expanding
Rotating
Illusion Type

Figure 3



Predicted log Head Movements
-3
-4
-5
medio - lateral
antero - posterior
Direction

Figure 12

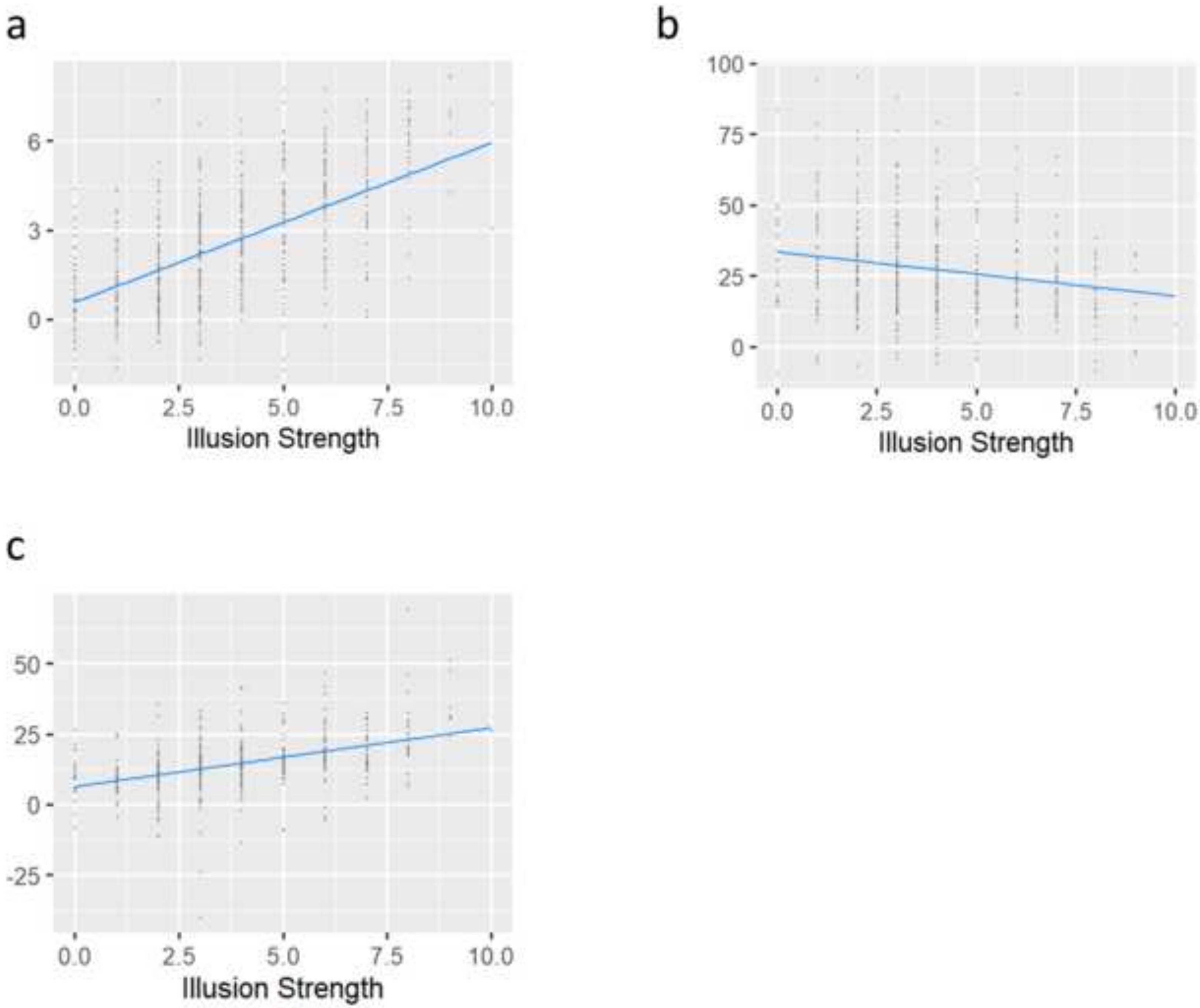
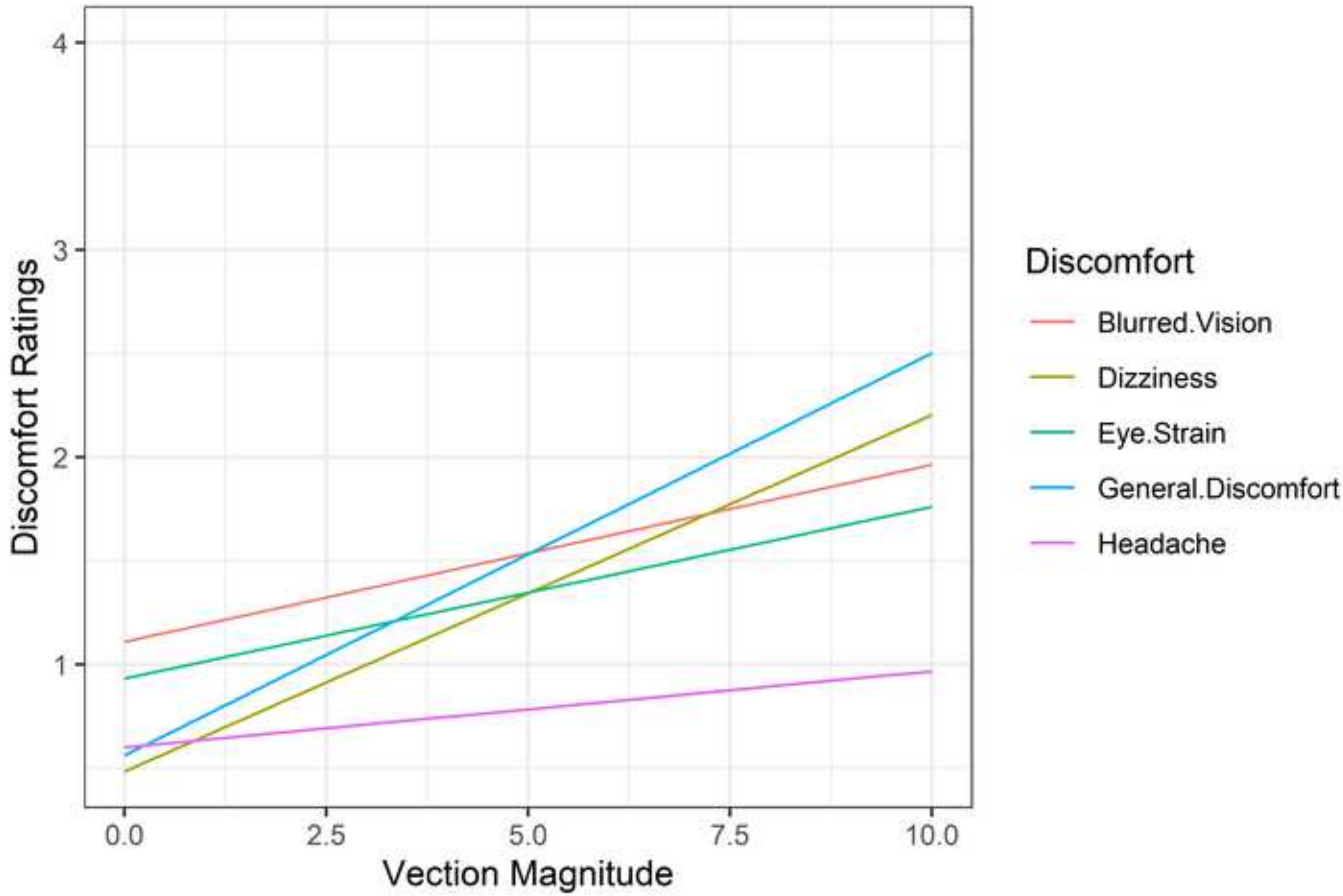

a
6
3
0
0.0
2.5
5.0
7.5
10.0
Illusion Strength
b
100
75
50
25
0
0.0
2.5
5.0
7.5
10.0
Illusion Strength
c
50
25
0
-25
0.0
2.5
5.0
7.5
10.0
Illusion Strength

Figure 13



Discomfort Ratings
4
3
2
1
0.0
2.5
5.0
7.5
10.0
Vection Magnitude
Discomfort
Blurred.Vision
Dizziness
Eye.Strain
General.Discomfort
Headache

Figure 14

Click here to access/download;Figure;figure14.tiff

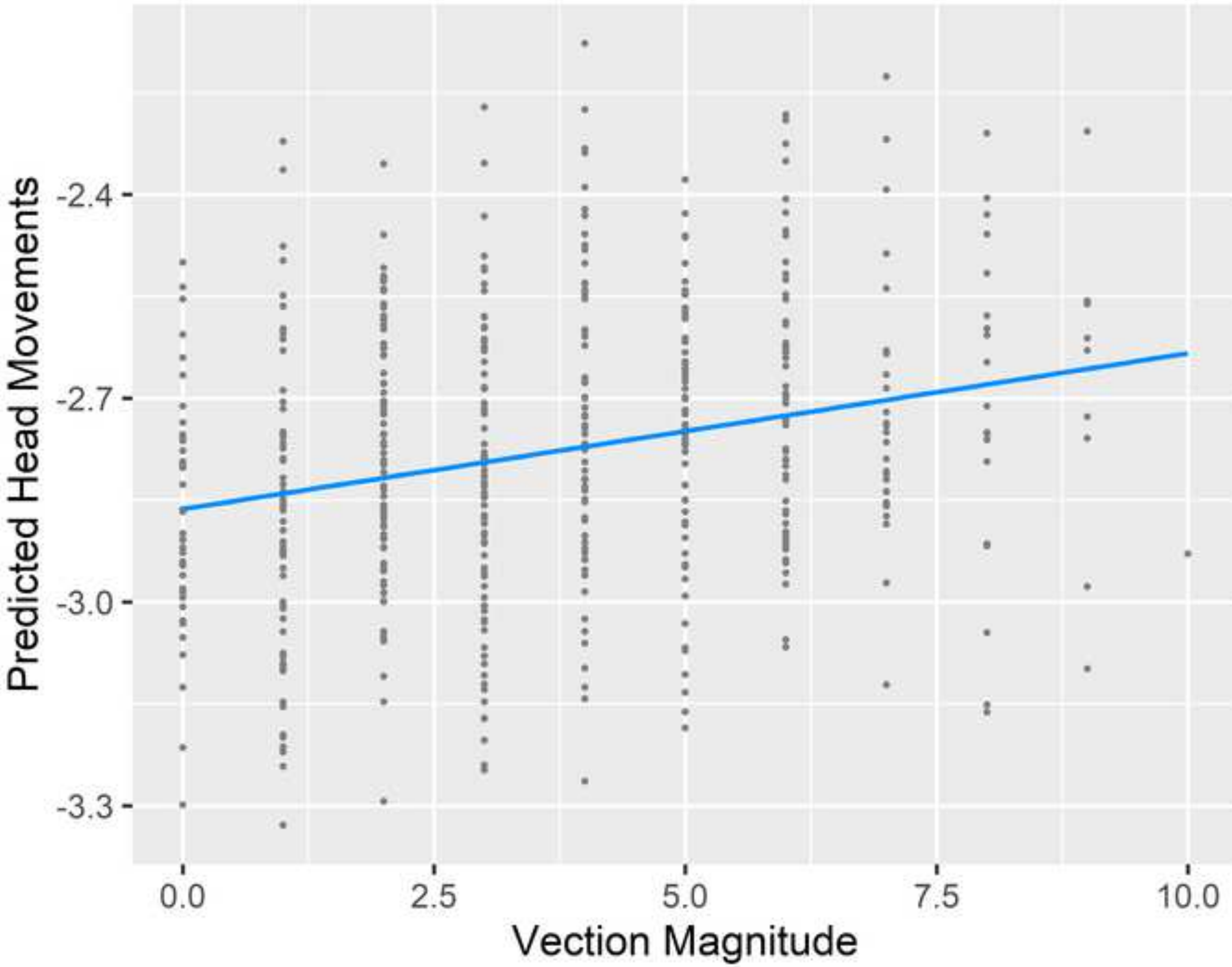


Figure 4

Click here to access/download;Figure;figure 4.tiff

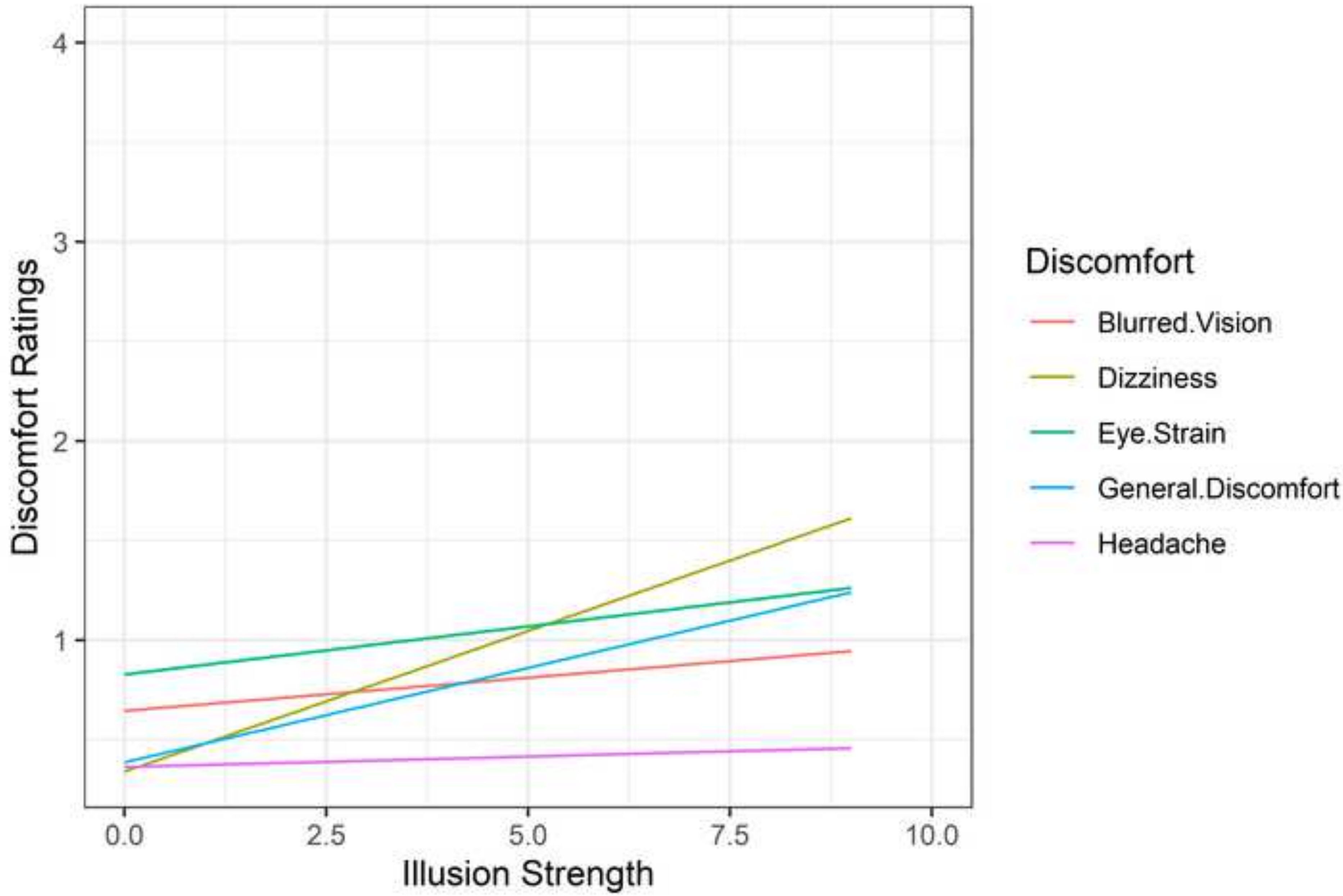
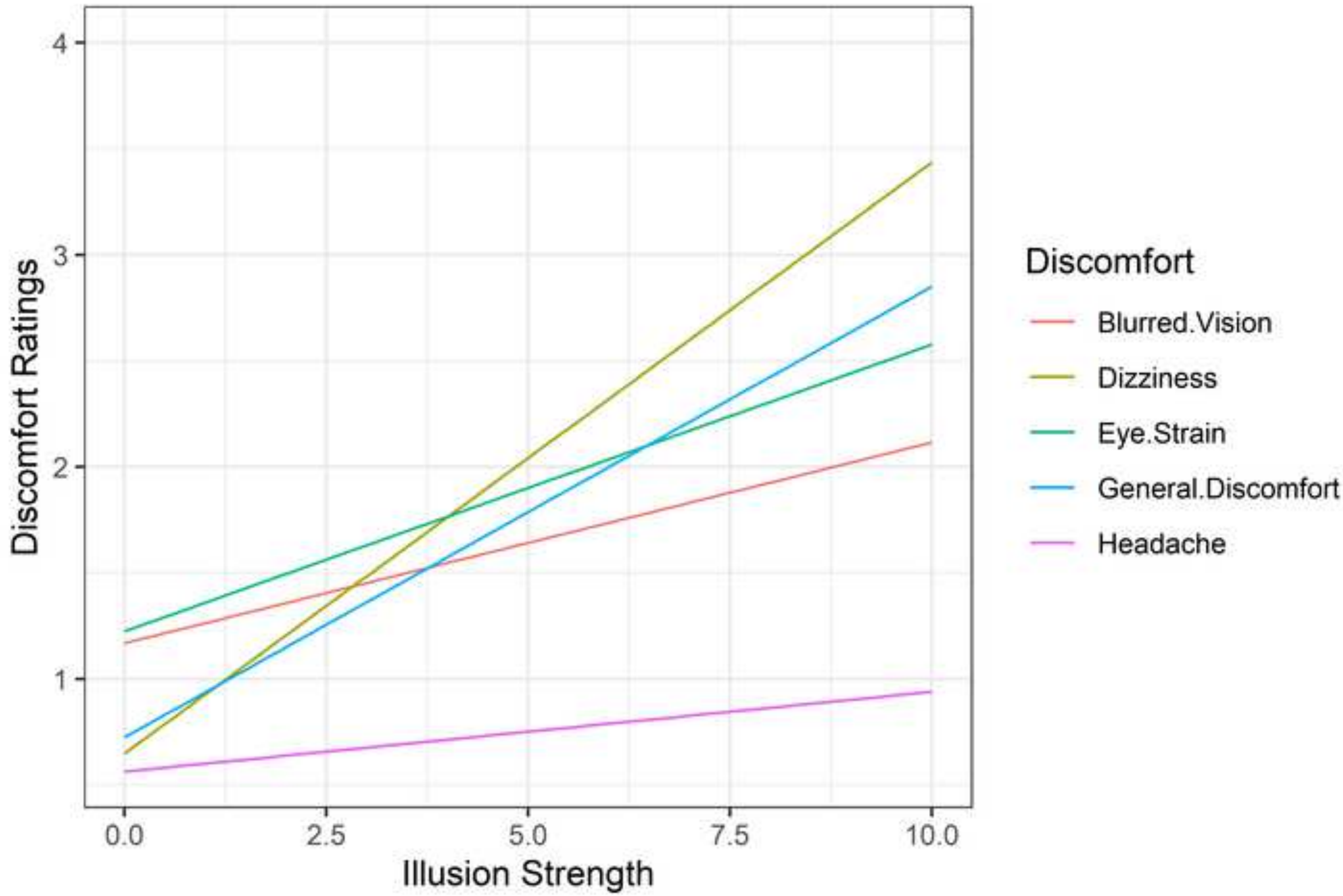
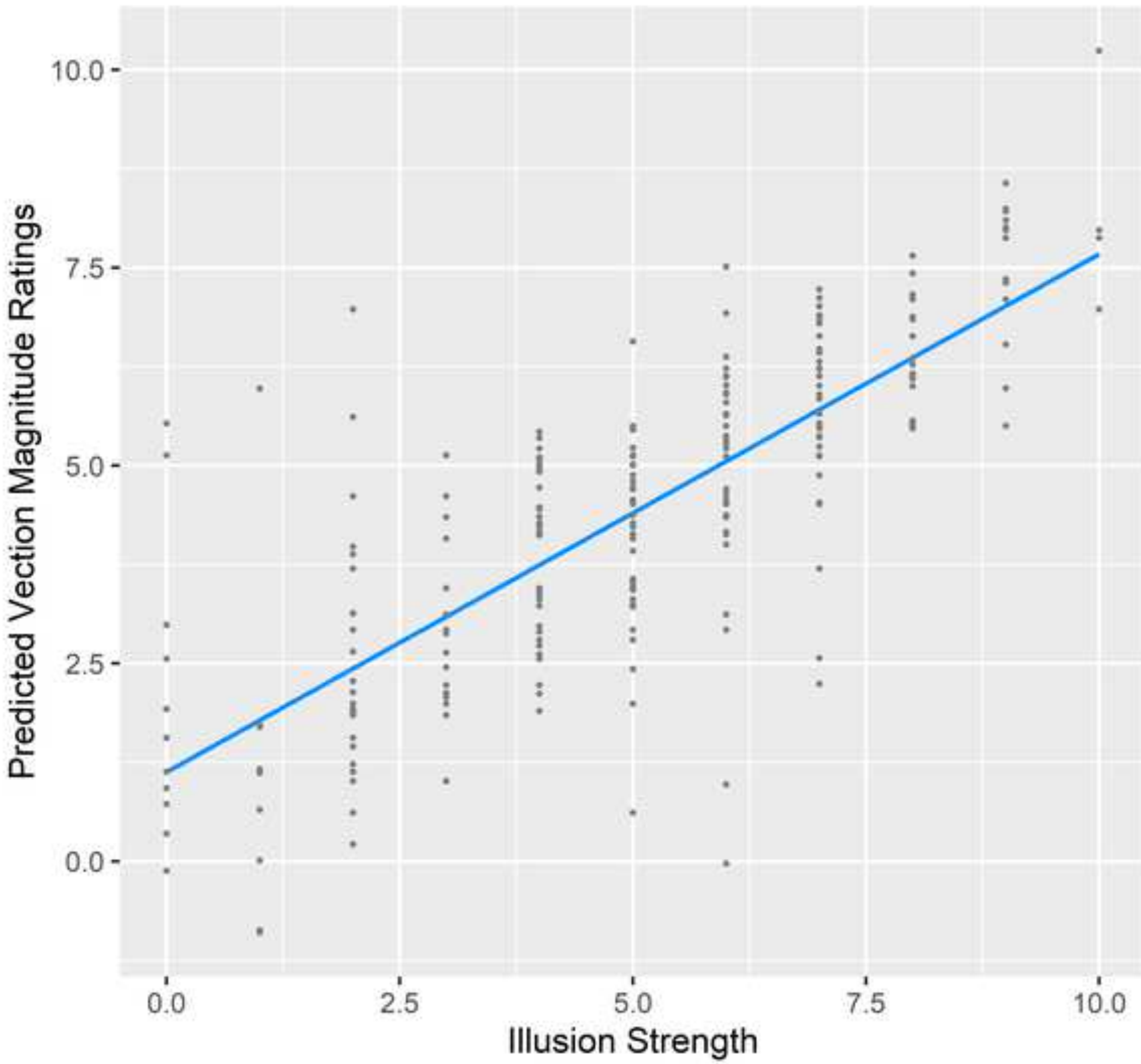


Figure 6



Discomfort Ratings
4
3
2
1
0.0
2.5
5.0
7.5
10.0
Illusion Strength
Discomfort
Blurred.Vision
Dizziness
Eye.Strain
General.Discomfort
Headache

Figure 7



Predicted Vection Magnitude Ratings
10.0
7.5
5.0
2.5
0.0
0.0
2.5
5.0
7.5
10.0
Illusion Strength

Figure 8

Click here to access/download;Figure;figure8.tiff

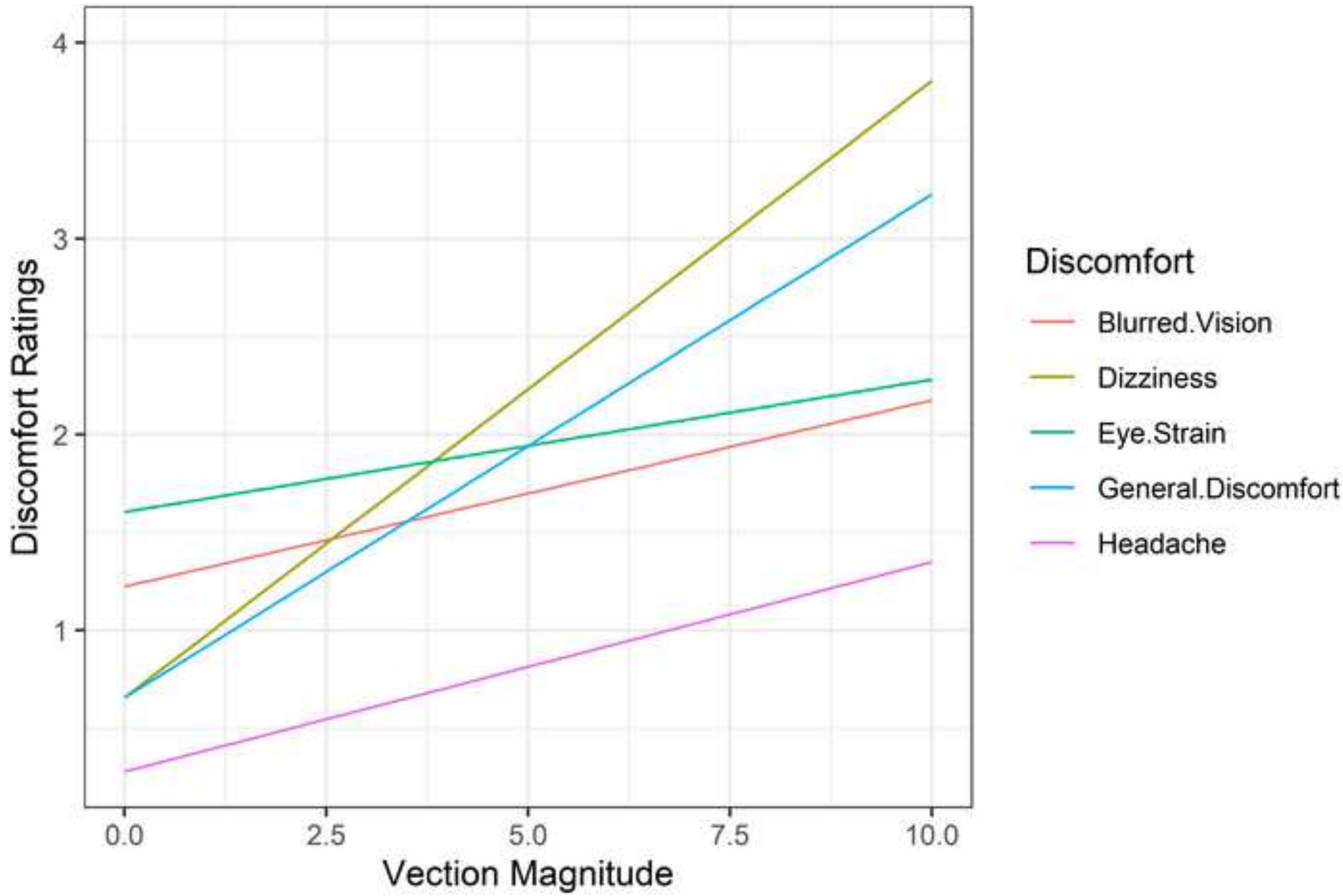


Figure 9

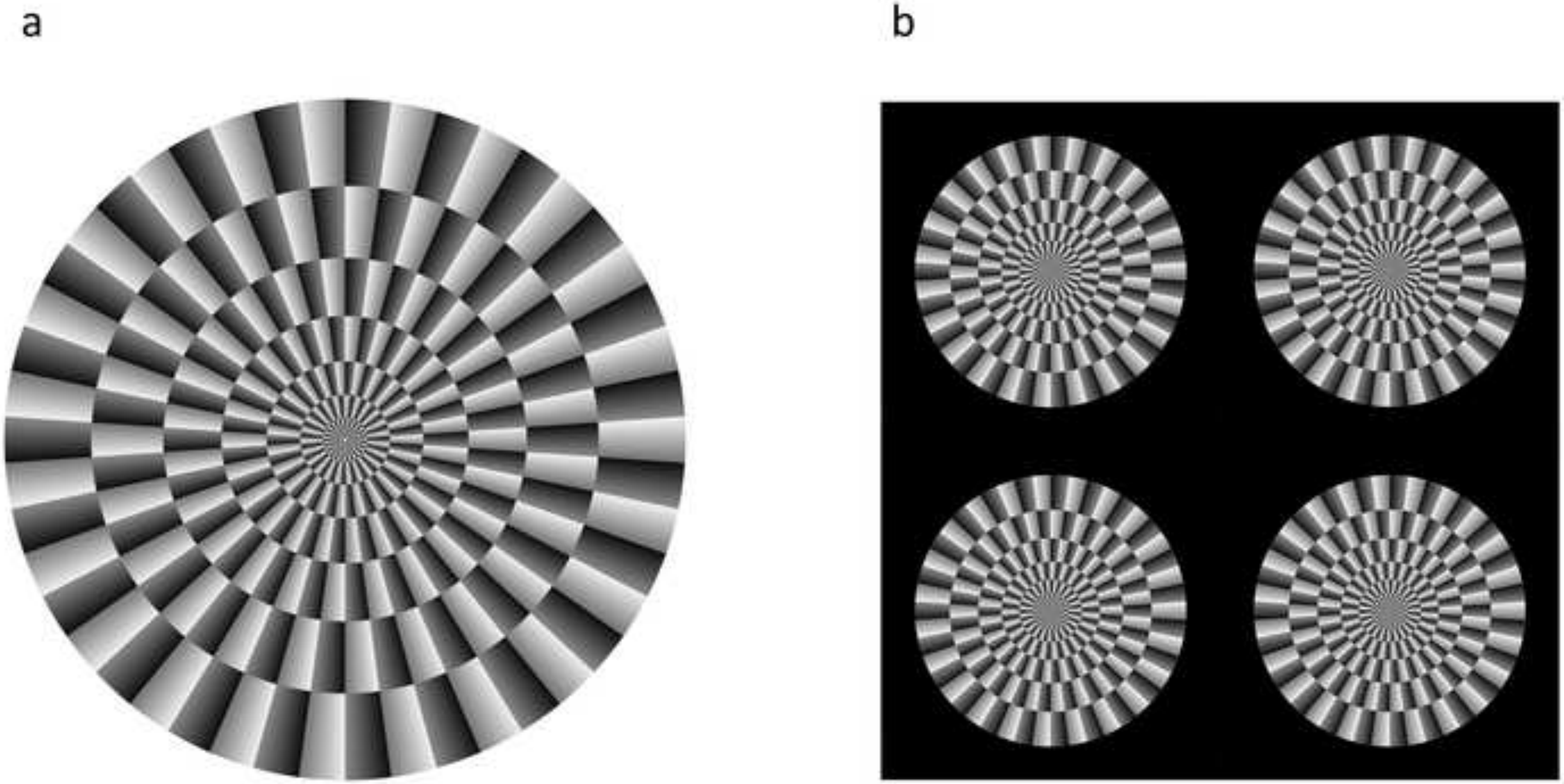


Figure 10

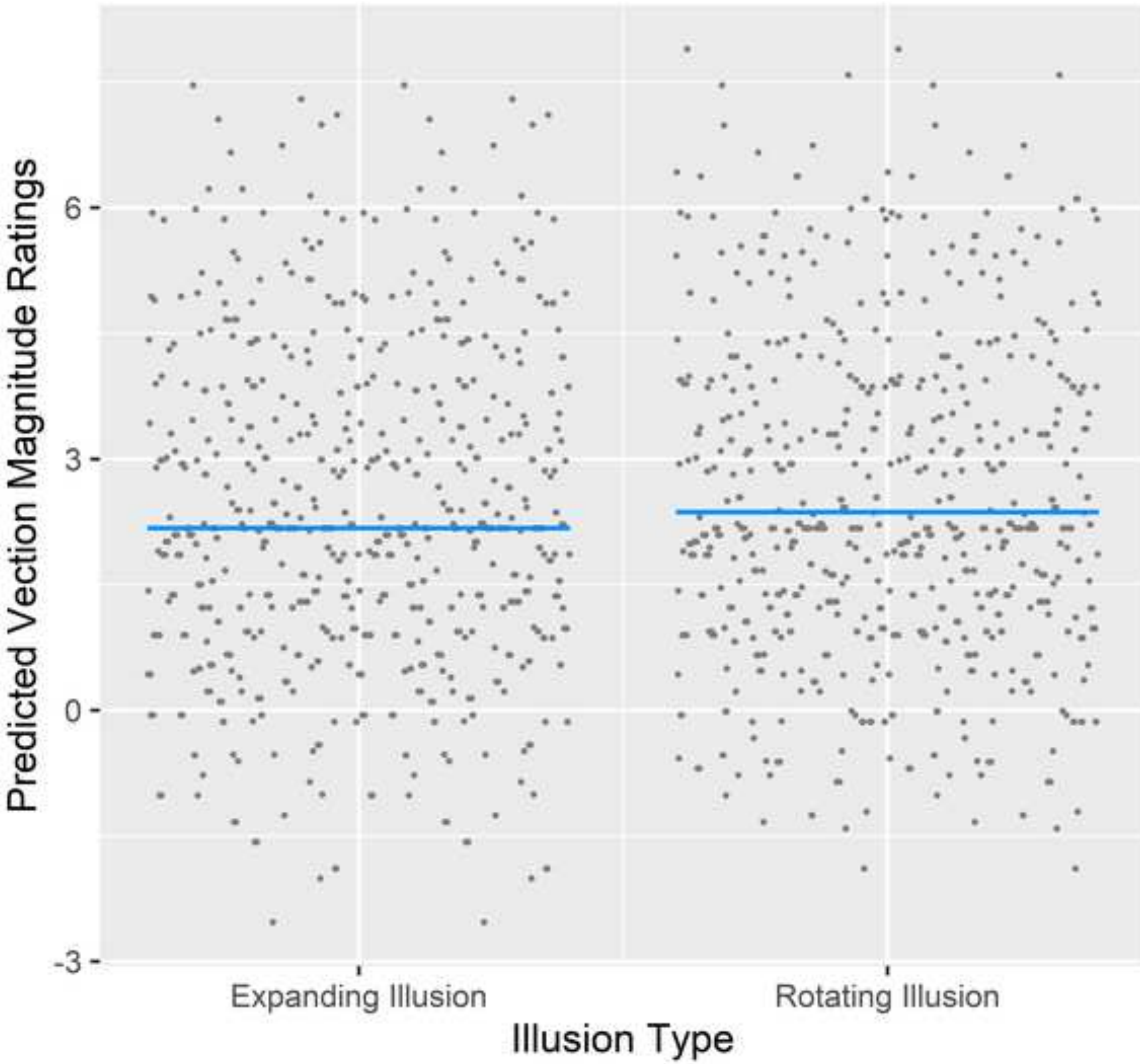
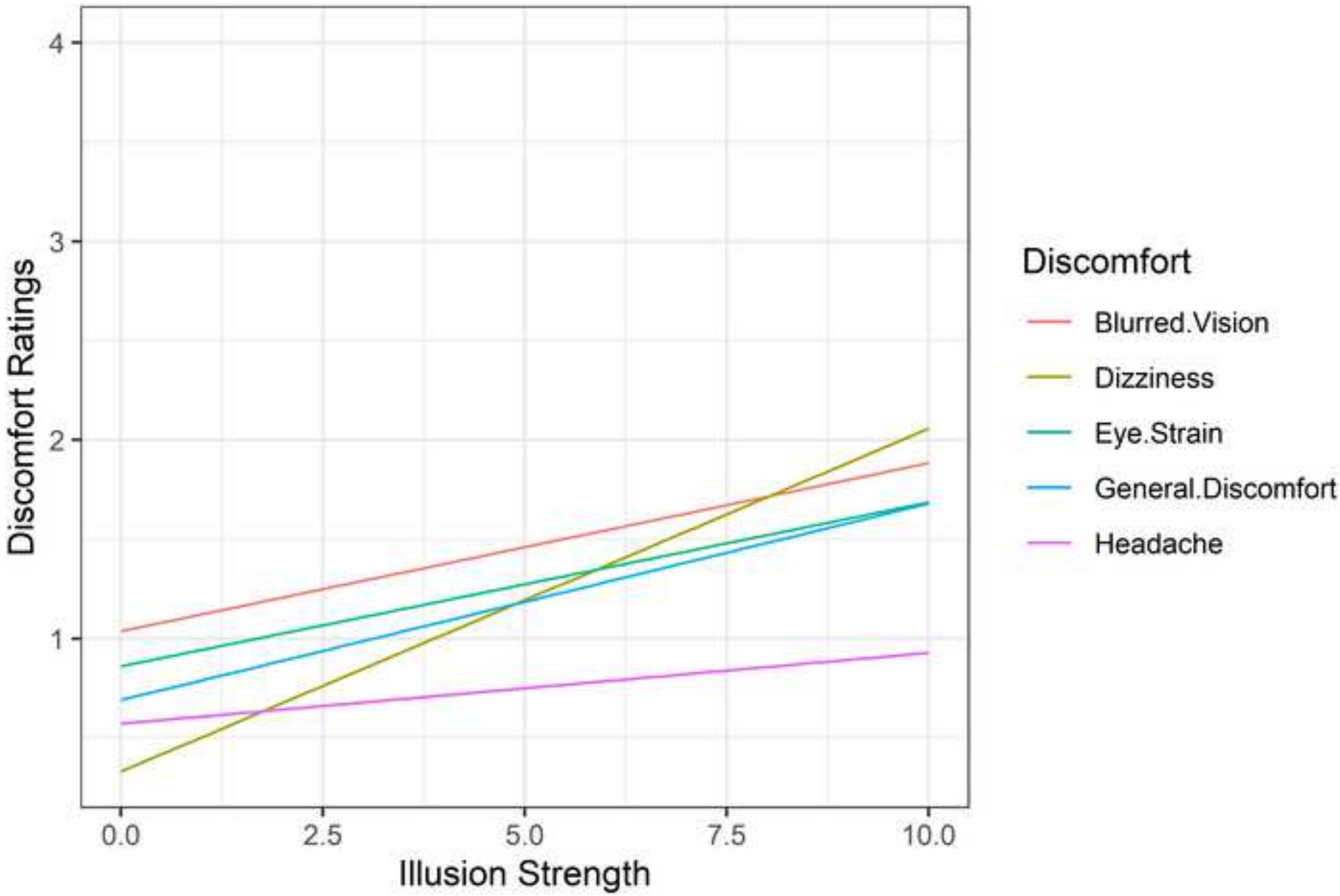

Predicted Vection Magnitude Ratings
6
3
0
-3
Expanding Illusion
Rotating Illusion
Illusion Type

Figure 11


Discomfort Ratings
4
3
2
1
0.0
2.5
5.0
7.5
10.0
Illusion Strength
Discomfort
Blurred.Vision
Dizziness
Eye.Strain
General.Discomfort
Headache

Discomfort	Illusion type		Illusion Strength	
	Mean (Std) for rotating vs. expanding stimuli	Test-statistic	Increase in discomfort measure per increase in illusion strength (Std Error)	Test- statistic
Experiment 1				
General Discomfort	0.84 (1.34) vs. 0.68 (1.89)	$F(1,782)= 4.32$, $p = .038$*, $f^2 = .005$, $\Delta BIC = -2.3$	0.09 (± 0.02)	$F(1, 809.92) = 20.96$, $p <.001$*, $f^2 = .04$, $\Delta BIC = 14$
Headache	0.42 (1.01) vs. 0.39 (0.96)	$F(1,782)= 0.37$, $p = .545$	0.01 (±0.01)	$F(1, 809.04) = 0.61$, $p = .435$
Blurred Vision	0.87 (1.66) vs. 0.68 (1.39)	$F(1,782)= 5.90$, $p = .015$*, $f^2 = .007$, $\Delta BIC = -0.8$	0.03 (±0.02)	$F(1, 809.98) = 2.33$, $p = .128$
Dizziness	0.95 (1.64) vs. 0.84 (1.47)	$F(1,782)= 2.12$, $p = .145$	0.14 (± 0.02)	$F(1, 809.13) = 45.58$, $p <.001$*, $f^2 = .07$, $\Delta BIC = 37.7$
Eye Strain	1.08 (1.77) vs. 0.95 (1.55)	$F(1, 782)= 3.15$, $p= .076$, $f^2 = .004$, $\Delta BIC = -3.4$	0.05 (± 0.01	$F(1, 804.93) = 5.39$, $p = .020$*, $f^2 = .02$, $\Delta BIC = -1.3$

* statistically significant at $p < 0.05$

Table 2 Click here to access/download;Table;Table 2.docx

Discomfort	Illusion type		Illusion Strength	
	Mean (Std) for rotating vs. expanding stimuli	Test-statistic	Increase in discomfort measure per increase in illusion strength (Std Error)	Test- statistic
Experiment 2				
General Discomfort	-	-	0.21 (± 0.03)	$F(1, 492.46) = 54.09$, $p <.001$*, $f^2 = .05$, $\Delta BIC = 45.4$
Headache	-	-	0.04 (± 0.02)	$F(1, 490.20) = 3.24$, $p =.073$
Blurred Vision	-	-	0.09 (± 0.03)	$F(1, 488.71) = 11.85$, $p < .001$*, $f^2 = .02$, $\Delta BIC = 5.5$
Dizziness	-	-	0.28 (± 0.03)	$F(1, 488.76) = 87.78$, $p < .001$*, $f^2 = .07$, $\Delta BIC = 75.1$
Eye Strain	-	-	0.14 (± 0.03)	$F(1, 499.94) = 16.73$, $p < .001$*, $f^2 = .01$, $\Delta BIC = 10.3$

* statistically significant at $p < 0.05$

Discomfort	Vection Magnitude		Vection Onset	
	Increase in discomfort measure per increase in vection magnitude (Std Error)	Test-statistic	Increase in discomfort measure per increase in vection onset (Std Error)	Test- statistic
Experiment 2				
General Discomfort	0.32 (± 0.05)	$F(1,312.81) = 46.52$, $p < .001$*, $f^2 = .18$, $\Delta BIC = 37.8$	-0.002 (± 0.004)	$F(1,309.08) = 0.19$, $p = .661$
Headache	0.14 (± 0.03)	$F(1,310.82) = 16.65$, $p < .001$*, $f^2 = .07$, $\Delta BIC = 10.5$	-0.005 (± 0.003)	$F(1,307.17) = 2.63$, $p = .106$
Blurred Vision	0.15 (± 0.04)	$F(1,306.22) = 12.98$, $p < .001$*, $f^2 = .10$, $\Delta BIC = 6.86$	-0.01 (± 0.004)	$F(1,302.92) = 6.33$, $p = .012$*, $f^2 = .17$, $\Delta BIC = 662.86$
Dizziness	0.39 (± 0.05)	$F(1,310.56) = 63.66$, $p < .001$*, $f^2 = .17$, $\Delta BIC = 52.80$	0.001 (± 0.005)	$F(1,306.88) = 0.07$, $p = .768$.
Eye Strain	0.17 (± 0.05)	$F(1,316.18) = 10.49$, $p < .001$*, $f^2 = .05$, $\Delta BIC = 4.60$	0.001 (± 0.005)	$F(1,312.47) = 0.01$, $p = .922$

* statistically significant at $p < 0.05$

Table 4 Click here to access/download;Table;Table 4new.docx

Discomfort	Illusion type		Illusion Strength	
	Mean (Std) for rotating vs. expanding stimuli	Test-statistic	Increase in discomfort measure per increase in illusion strength (Std Error)	Test- statistic
Experiment 3				
General Discomfort	1.05 (1.91) vs. 0.95 (1.89)	$F(1,1632)=2.72$, $p= .099$	0.10 (± 0.02)	$F(1, 1678.9) = 35.26$, $p <.001$*, $f^2 =.01$, $\Delta BIC = 27.57$
Headache	0.67 (1.47) vs. 0.69 (1.46)	$F(1,1632)=0.16$, $p= .691$	0.04 (± 0.01)	$F(1, 1691.2) = 6.32$, $p = .012$*, $f^2= .0004$, $\Delta BIC = -1.1$
Blurred Vision	1.33 (2.09) vs. 1.27 (2.02)	$F(1,1632)=1.00$, $p= .317$	0.08 (± 0.02)	$F(1, 1663.3) = 29.24$, $p <.001$*, $f^2 = .02$, $\Delta BIC = 21.6$
Dizziness	0.92 (1.73) vs. 0.83 (1.64)	$F(1,1632)= 1.91$, $p= .167$	0.17 (± 0.02)	$F(1, 1686.2) = 126.72$, $p <.001$*, $f^2 = .08$, $\Delta BIC = 114.9$
Eye Strain	1.19 (1.94) vs. 1.06 (1.84)	$F(1,1632)=6.11$, $p= .014$*, $f^2 = -0.01$, $\Delta BIC = -1.4$.	0.08 (± 0.01)	$F(1, 1661.3) = 35.01$, $p <.001$*, $f^2 = .02$, $\Delta BIC = 27.2$

* statistically significant at $p < 0.05$

Table 5

Click here to access/download;Table;Table 5.docx

Discomfort	Vection Magnitude		Vection Onset		Vection Duration	
	Increase in discomfort measure per increase in vection magnitude (Std Error)	Test-statistic	Increase in discomfort measure per increase in vection onset (Std Error)	Test- statistic	Increase in discomfort measure per increase in vection onset (Std Error)	Test- statistic
Experiment 3						
General Discomfort	0.19 (± 0.03)	F (1,997.47) = 38.84, p <.001*, f^2 = 0.02, ΔBIC = 31.4	0.001 (± 0.003)	F (1,995.84) = 0.03, p =.852	0.007 (± 0.005)	F (1,805.64) = 1.68, p =.196
Headache	0.02 (± 0.03)	F (1,976.37) = 0.65, p =.420	-0.002 (± 0.002)	F (1,996.08) = 0.96, p =.328	-0.004 (± 0.004)	F (1,593.09) = 0.63, p =.428)
Blurred Vision	0.07 (± 0.03)	F (1,996.64) = 6.55, p = .011*, f^2 = 0.01, ΔBIC = -0.3	0.0003 (± 0.002)	F (1,989.72) = 0.02, p =.894	0.003 (± 0.005)	F (1,897.40) = 0.31, p =.581
Dizziness	0.21 (± 0.03)	F (1,985.11) = 49.38, p < .001*, f^2 = 0.04, ΔBIC = 41.3	0.005 (± 0.003)	F (1,997.61) = 3.41, p = .065	0.001 (± 0.005)	F (1,650.90) = 0.05, p =.831
Eye Strain	0.06 (± 0.03)	F (1,992.96) = 4.62, p = .032*, f^2 = 0.04, ΔBIC = 41.2	0.001 (± 0.002)	F (1,984.68) = 0.18, p =.668	0.006 (± 0.005)	F (1,943.46) = 1.52, p =.218

* statistically significant at p < 0.05

Conflicts of interest

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

Authors' contribution

Katharina Margareta Theresa Pöhlmann: Conceptualization, Methodology, Software, Validation, Data Curation, Writing-Original Draft, Writing-Review & Editing, Visualization, Supervision, Project Administration **Julia Föcker:** Conceptualization, Writing-Review & Editing **Patrick Dickinson:** Conceptualization, Software, Writing-Review & Editing, Funding Acquisition **Adrian Parke:** Conceptualization, Writing-Review & Editing, Funding Acquisition **Louise O'Hare:** Conceptualization, Methodology, Validation, Data Curation, Writing-Review & Editing, Funding Acquisition

The Relationship between Vection, Cybersickness and Head Movements Elicited by Illusory Motion in VR

Title: The Relationship between Vection, Cybersickness and Head Movements Elicited by Illusory Motion in Virtual RealityC

Running Title: *The Relationship between Vection, Cybersickness and Head Movements Elicited by Illusory Motion in Virtual Reality*

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Key words: Perception, virtual reality, vection, discomfort, motion illusion, cybersickness

Abstract

Cybersickness is an unpleasant side effect of Virtual Reality and is often detrimental to a user's experience. It shows a complex relationship to vection (illusory self-motion) as well as postural instability. Three experiments were conducted presenting both expanding and rotating colourful optimised Fraser Wilcox illusions as well as grey-scaled controlled versions of the illusions. Cybersickness and vection were reported and head movements in medio-lateral and anterior-posterior direction were recorded. The experiments found that perceived visual motion (illusory motion) is sufficient to elicit vection in the absence of any stimulated visual motion. The strength of motion perceived in the illusions was related to the experience of cybersickness and vection, with illusions that were perceived as moving more eliciting stronger experiences of both. Surprisingly, rotating illusions were continuously perceived as moving more compared to expanding motion illusions, which could be related to missing stereoscopic motion-in-depth cues. Head movements were unrelated to any stimuli properties, suggesting that the motion signal elicited by the illusions might not have been strong enough to cause postural instability. Finally, dizziness has been identified as the possible link between cybersickness, vection and head movements supporting sensory conflict as well postural instability theories of cybersickness.

Key words: Perception, virtual reality, vection, discomfort, motion illusion, cybersickness

1 Introduction

The use of head-mounted displays (HMDs) to experience virtual reality (VR) has become increasingly popular with applications in entertainment (e.g. *Half Life Alyx*), therapy [1–4] and training [5–7]. However, HMDs can also cause adverse symptoms often referred to as cybersickness [8,9]. These can be motion sickness like symptoms, such as nausea, dizziness and disorientation, and visual stress symptoms, such as headache, eye strain or difficulty focusing [9,10]. Cybersickness is impacted by individual differences, to the extent that some individuals are unable to use VR headsets at all as they cause them too many adverse symptoms, potentially limiting wider uptake, and the commercial success of VR applications. Discomfort in virtual environments is often related to explicit visual motion, either the scene being moved around the observer, or objects moving around in the scene. Stereoscopic (3D) displays prove challenging for the visual system, due to the conflict between vergence and accommodation, which can lead to discomfort in the viewer. Vergence and accommodation are two processes involved when viewing an object in space. Vergence is the simultaneous movement of the pupils towards or away from each other to focus on the object and accommodation is defined as the process of changing the focal length of the ocular lens to fixate on the object [11–13]. An alternative potential cause of motion sickness in general as well as cybersickness is postural instability, due to mechanism for maintaining balance (the vestibular system) being undermined for example, in unfamiliar virtual environments [14,15]. HMDs in particular can cause a conflict between sensory modalities - the visual system indicates the observer is moving, while at the same time the vestibular system indicates the observer is stationary, leading to discomfort. The HMD completely occludes the surrounding environment (e.g. ground plane) thereby eliminating any anchor points that could help orient and stabilise the observer [16]. This complete occlusion of the real world is one of the main differences between HMDs and other visual displays (e.g. LCD, flat displays or screen projectors). Additionally, some advantages of HMDs compared to desktop displays have been discussed, such as their wider FOV, they allow for stereoscopic presentation, for more movement in the user and they allow for a complete occlusion of the surrounding environment, which can increase immersion and presence, which in turn has beneficial effects on treatment and training outcomes as well as game enjoyment [17,18]. Interpretation of the motion is important to the subjective experience of cybersickness. When visual motion is interpreted as scene motion (background motion) rather than object motion (foreground motion) it can lead to the illusion of self-motion in the stationary observer, called vection [8,19–22]. Traditionally vection was believed to cause or at least precede cybersickness [23], with multiple studies finding a positive relationship between vection and discomfort [24–26]. However, other research has found contradictory results indicating that vection does not necessarily cause cybersickness or is even related to it at all [8,27–29], suggesting a more complex relationship between vection and cybersickness than was previously believed.

One important aspect that can potentially affect cybersickness and vection is the direction of motion. As the rate of change of the accommodation-vergence conflict affects discomfort, this may be particularly problematic for simulation motion-in-depth [30]. Vection has been shown to be stronger for motion directions that an individual has more experience with [31]. Bubka and colleagues [31] compared illusory self-forward motion and backward motion and found stronger experiences for visual stimuli eliciting self-forward motion. Therefore, when comparing lateral motion and motion-in-depth more vection for stimuli moving in depth would be expected (specifically, forwards).

Research suggest that the experience of vection does not require explicit motion, as perceived stimulus motion can also elicit vection in the absence of any physical stimulus motion [20,32,33]. The current experiments aim to add to the existing research by investigate whether illusory motion, which does not contain any physical motion energy, can cause vection as well as cybersickness. We used optimised Fraser Wilcox illusions in the following experiments, as they elicit apparent motion from a stationary image [34]. These illusions appear to be moving (rotating or expanding) even though they are completely stationary. Unlike optic flow stimuli, they appear at a constant depth, thus could potentially minimising any systematic effects of the discrepancy between accommodation and vergence.

The illusions are made up of repetitive patterns with varying luminance and contrast profiles. It is believed that the relationship of luminance contrast of these static elements induces the illusory drift motion, with the direction of the illusory motion being dependent on the intensity relationship of the elements in the pattern [35,36]. This luminance and contrast relationship of the different elements is also believed to trick the brain into seeing the illusory motion, with motion detectors in the brain responding to the stationary patterns in a similar way to how they would respond to actual motion [35,37,38]. The specific eye movement patterns that induce the illusion of motion are still unclear, therefore a free viewing condition is recommended when presenting the illusions [39]. There is an effect of eccentricity on the strength of these illusions; they are strongest when presented in the periphery [34,40–42]. The illusory motion is perceived as stronger for stimuli in which many pattern elements are combined together, these elements are of varying sizes and they are organised in a circular arrangement. The *rotating snake illusion* by Akiyoshi Kitaoka combines all these illusion enhancing properties (see Figure 1b; [39,42]). Vection research so far has mainly focused on global motion stimuli, however, local rotation has been shown to be able to affect roll vection elicited by a global rotation stimulus [43]. Locally rotating elements can enhance and inhibit the experience of vection depending on their congruency with the global motion stimulus [43]. The illusions in the current experiments are composed of multiple parts of visual illusion each of which can independently induce illusory rotation or expansion. Based on Nakamura's work we hypothesised that these local motion signals would be able to elicit a sensation of vection even though weaker than if elicited by a global motion stimulus.

Several other factors can influence the experience of cybersickness, such as the speed of the perceived motion [13,44,45], its size [46,47], exposure time [48–50] and acceleration [51,52]. Similarly these same factors can also affect vection: speed [53–56], size [57–60] and exposure time [61], as well as acceleration [62]. As the stimuli we use are static motion illusions, this helps control for several of these factors.

Head movements were also measured in the current study as an objective correlate of the observers' subjective experiences. This is important, as vection can lead to postural instability, whereby moving visual input such as expanding or contracting optic flow causes postural sway in observers [63].

We conducted three experiments using HMDs to investigate the relationship between cybersickness, head movements and vection in relation to optimised motion illusions. The motion illusions used in this study were rotating or expanding, eliciting either planar motion or motion-in-depth respectively. Motion-in-depth causes more discomfort in stereo displays compared to planar motion [13]. It was therefore expected that expanding motion illusions would cause more discomfort in the observer compared to rotating motion illusions. It was also expected that motion illusions that caused more discomfort in the observer would lead to more head movements in general. Postural sway is experienced in the same or opposite direction of the presented visual stimulus [64]. Therefore, it was expected that expanding motion illusions, eliciting motion-in-depth would lead to more anterior-posterior head movements, whereas rotating motion illusions which exhibit planar motion would lead to more medio-lateral head movements.

In Experiment 1 we used rotating and expanding motion illusions that were colourful art works as stimuli to investigate effects of motion direction on cybersickness and head movements. Additionally, illusion strength was measured to identify the effect of the strength of the perceived motion on the two phenomena. Experiment 2 introduced vection as a link between cybersickness and head movements. Investigating the effect of expanding colourful motion illusions on cybersickness, vection and head movements as well as the effect of illusion strength on the three. For Experiment 3 grey scaled rotating and expanding motion illusions were designed as stimuli to ensure that effects on cybersickness, vection and head movements were independent of colour or design of the illusions.

2 Experiment 1

The aim of the first experiment was to investigate the relationship between head movements and discomfort induced by visual motion illusions in VR. The illusions used in the first two experiments have both sawtooth and stepwise luminance profiles and are artworks created by Akiyoshi Kitaoka (see Figure 1), designed to elicit the strongest possible motion illusion [36,42,65,66]. Sawtooth luminance profiles consist of repeated luminance gradients (black → dark grey → light grey → white; see e.g. Figure 1a,c,d and 8) with illusory motion being perceived from dark to light shading and appearing in a constant direction guided by these patterns [34,42,66,67]. The stepwise design is composed of luminance defined micropatterns, each having four adjacent regions of different luminance (black → dark grey →white → light grey; see Figure 1b), when this pattern is repeated, a strong motion can be perceived in this direction [42,67].

2.1 Methods

2.1.1 Observers

Thirty-one observers with normal or corrected-to-normal vision took part in the study. Data from one observer was excluded from the analysis as they felt nauseated half-way through the experiment and withdrew resulting in a sample size of 30 observers. Sample size was based on previous research [68,69]. They ranged in age from18 to 39 years (M = 21.9 years, SD = 4.33). For all experiments (Experiment 1, 2 and 3), written informed consent was obtained observers prior to participating in the experiment with the study being 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.

2.1.2 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. An Oculus Rift Headset (CV1) was used to present the stimuli. This headset covers 90° of the FOV of the user and completely occludes the rest of their surroundings. The headset consists of two separate Pentile OLED displays one for each eye with a resolution of 1080x1200 pixel and a final resolution of 2160x1200 pixel combined. It has a refresh rate of 90Hz and yields a 110° field of view. Stimuli were presented using 64-bit Unity 2018.2 (Unity Technologies, San Francisco, USA), using the Oculus platform. The virtual environment is made up of a completely black surround with the motion illusions displayed on a virtual screen in front of the observer.

2.1.3 Stimuli

Fourteen simple geometric motion illusions served as stimuli in Experiment 1 (for examples see Figure 1), they were created by Akiyoshi Kitaoka [70] and can be classified as optimized Fraser-Wilcox illusions [34,67]. They were designed to elicit the strongest possible illusion of motion. The 14 motion illusions were chosen for this study as they were rated highest on illusion strength out of 22 stimuli in a preceding pilot study (20 observers, see Supplementary Material 1 for details). The pilot study also aimed to determine the optimal distance for stimulus presentation. The optimal distance was defined as the distance at which observers were able to see most movement in the presented patterns, hence, at which distance the motion illusion was the strongest. The data collected in the pilot study showed considerable individual differences between the observers with regards to the selected distances for image presentation as well as strong differences between the different stimuli. Therefore, it was decided that observers can choose their optimal distance for each stimulus, resulting in the images taking up between 4.3° and 33.4° of the visual field ($M = 13.45°$, $SD = 6.26°$). Thus, we ensured that all stimuli were presented at a distance inducing the strongest possible motion illusion for each observer. The images either induced the illusion of a rotating or an expanding/contracting motion. Stimuli contain 4 high spatial frequency images and 3 low spatial frequency images for both rotating and expanding illusions (see Figure 1). The used stimuli are uncontrolled colourful versions.

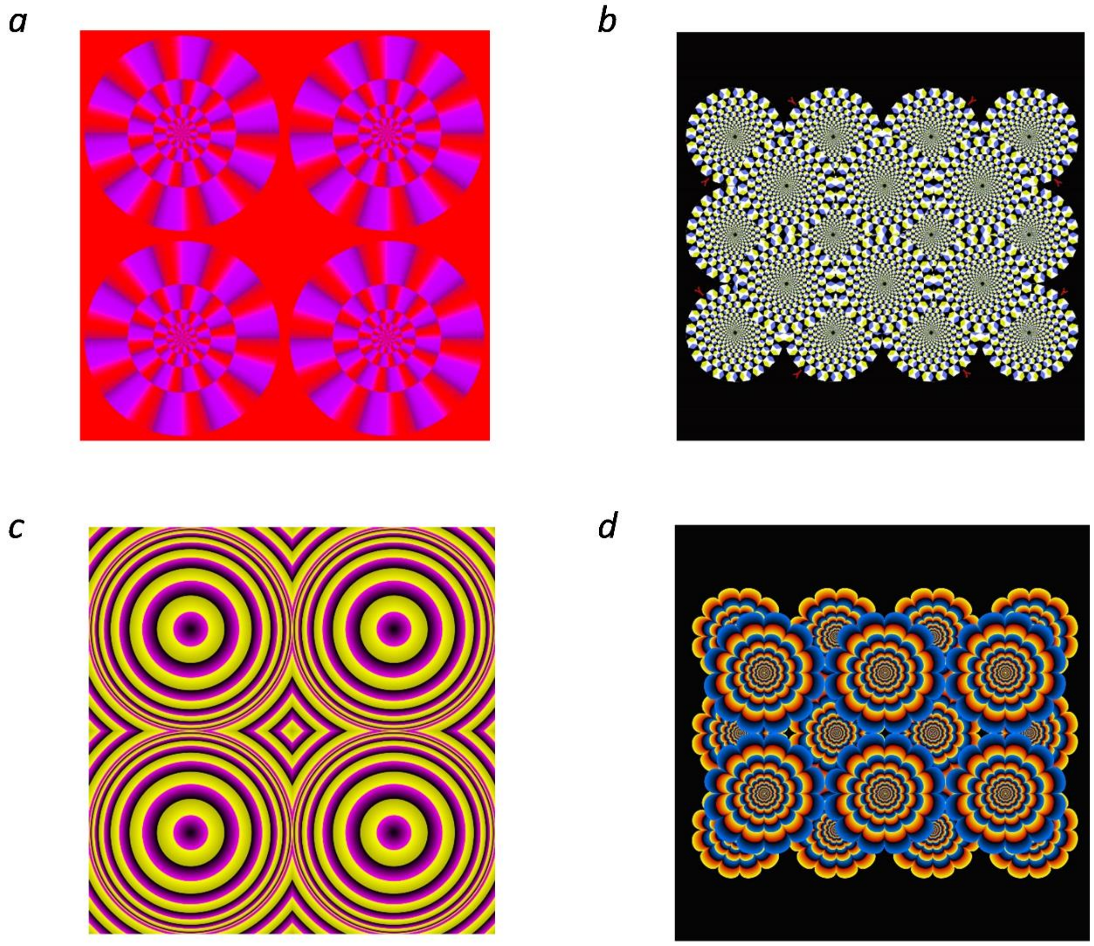

Figure 1: Examples of the used motion illusion stimuli. A) and b) give examples of two rotating motion illusions whereas c) and d) show two examples of expanding motion illusions. A) and c) are examples of low spatial frequency stimuli and b) and d) are examples of high spatial frequency stimuli.

2.1.4 Measures

For each stimulus observers rated the perceived illusion strength as well as their experienced discomfort (general discomfort, headache, blurred vision, dizziness and eye strain) on a 11-point

Likert scale, with 0 representing no motion/no discomfort and 10 representing the strongest experience of illusory motion/discomfort. The chosen discomfort measures were based on the Simulator Sickness Questionnaire (SSQ, [71]). This brief verbal assessment was performed to obtain illusion strength and discomfort measures for each distinct stimulus. 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.

2.1.5 Procedure

After giving informed consent for the experiment 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). The game play lasted for around 10 -15min, none of the observers withdrew at this point of the study and were happy to continue on to the experiment. Observers were shown examples of the type of motion illusions they were going to view in the VR. They were instructed to not focus on any specific point on the image but rather “wander with their eyes over the image” to perceive most movement in the illusion. They were also informed that the motion illusion will most likely be strongest in their periphery. The environment within the experiment consisted of a completely black surround, which prevents any distraction from task irrelevant visual input. For the duration of the experiment observers were asked to stand as still as possible. The experiment consisted of two parts. Both started with the presentation of text informing the observer that pressing the “A” button will allow them to move on. At this point observers were instructed to try out the different settings of the headset to get the text as focused as possible, such as setting the distance of the display to the face and setting the distance between the two lenses. When observers were satisfied with the focus of the headset, they could initiate the training by pressing a button on the controller. In the first part, the 14 motion illusions were presented one after the other and the observers could move them back and forth to determine the distance at which they perceived most movement in the illusion, we will refer to this as the optimal distance from now on. When satisfied with the distance they moved on to the next stimulus. In the second part of the experiment the motion illusions were presented at the previously chosen distance for 30 seconds, after which they disappeared, and observers verbally rate the strength of the illusion and the level of discomfort (general discomfort, headache, blurred vision, dizziness, eye strain) they experienced. After rating each stimulus for illusion strength and discomfort level the researcher prompted the observer to initiate the next trial. The motion illusions were presented in the same order for each observer in the first part of the experiment and in random order for the second part of the experiment.

2.1.6 Analysis

For Experiment 1,2 and 3 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. The data were read into MATLAB version R2018a (Mathworks, Natick, USA) for analyses. The time sequence for the duration of each of the 14 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. 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 stimulus and observer were calculated. Resulting in two displacement scores which served as a measure to estimate the head movements for each observer for each of the 14 stimuli in both medio-lateral and anterior-posterior direction. This analysis, however, does not take temporal dynamics into account, which is why a detrended fluctuation analysis (DFA) was performed on the head movements in all experiments resulting in DFA alpha values greater or very close to 1 indicating that head movement data is non-stationary, for review see for example [72–74]. The relationship between the DFA alpha values and illusion strength, illusion type, cybersickness and vection magnitude can be found in the supplementary Material 2, which is similar to the relationships found for maximum displacement of head movements.

Statistical analysis was conducted using R 3.5.3 [75] using the "(g)lmer" function of the *lme4* package [76] to perform linear mixed effect analyses. 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 [77]. In the following experiments observer was included as a random effect in the models to account for variability in effects across observers. Stimulus was also included as a random effect in a first round of analyses was then, however, dropped as a random effect in the final models due to low variance in the random factor. For linear mixed-effects models, p-values of overall effects were determined using conditional F tests with Satterthwaite's approximation to degrees of freedom [78] using a Type III ANOVA, as implemented in the "anova" function from the *lmerTest* package [79]. Following the examples of Winter [80], the model was compared to a null model missing the variable of interest using a likelihood ratio test, in order to obtain a difference in Bayes Information Criterion (ΔBIC), to estimate the strength of the evidence for a particular effect. The model with the lowest BIC value is determined as the best fit model. Differences lower than 2 between two models are very weak and can be ignored or have to be interpreted with care. BIC values reported here represent the difference between the full models' and the null models' BIC values. A negative difference in BIC indicates evidence in support of the null model, rather than the alternative model [81,82]. Models were created for fixed effects that showed a significant effect on the outcome variable. As an additional measure of effect size Cohen's f^2 was calculated for fixed effects showing a significant effect using the "r.squaredGLMM" of the *MuMIn* package [83]. R^2 for the full an null model were calculated and used to determine Cohen's f^2 of the fixed effects: $f^2_{\text{significant effect}} = \frac{R^2_{\text{full model}} - R^2_{\text{null model}}}{1 - R^2_{\text{full model}}}$ [84], with $f^2 \geq 0.02$ representing small, $f^2 \geq 0.15$ representing moderate, and $f^2 \geq 0.35$ representing large effect sizes [85]. For all models Satterthwaite's approximation was used to adjust the degrees of freedom for violations of sphericity [86,87]. Figures were produced using the "visreg" function within the *visreg* package [88].

2.2 Results

2.2.1 Expanding vs Rotating

2.2.1.1 Illusion strength

Illusion strength was predicted using a linear mixed effect model including illusion type (expanding, rotating) as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiments looks as followed:

$$Model = lmer\ (Illusion\ Strength \sim Illusion\ Type + (1|Observer))$$

A significant effect of illusion type on illusion strength ratings was found, $F(1,782)=39.69$, $p< .001$, $f^2 = .05$, $\Delta BIC = 32.10$. Rotating motion illusions were rated significantly higher on illusion strength (M = 4.31, SD= 2.48) compared to expanding motion illusions (M = 3.53, SD = 2.35), suggesting that observers perceived stronger motion in rotating motion illusions, see Figure 2.

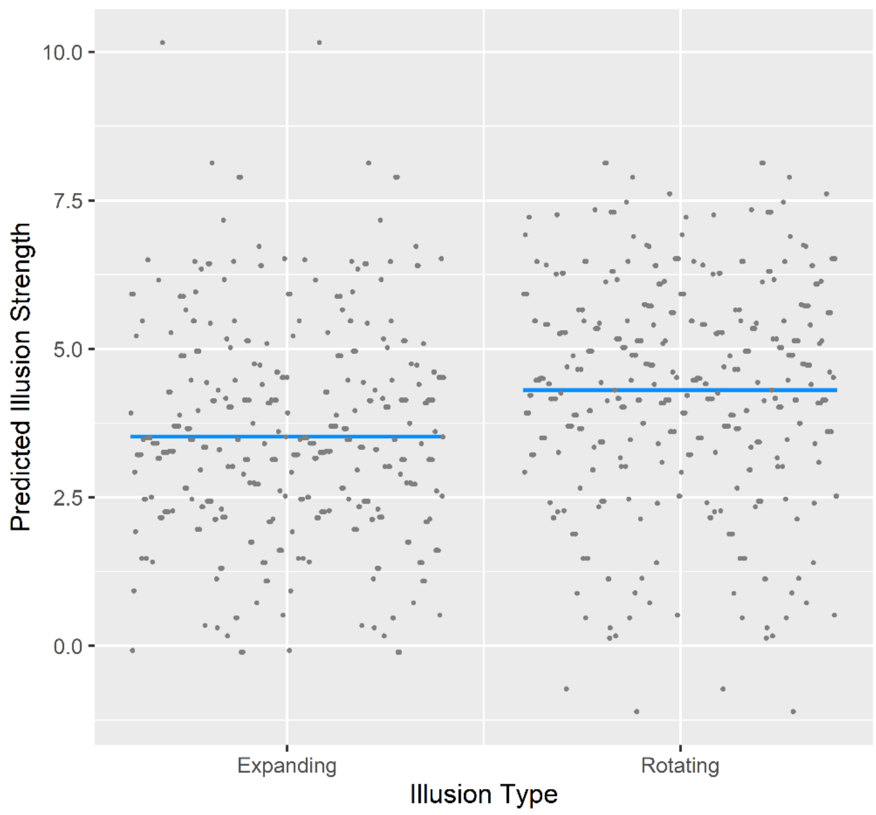

Figure 2: Experiment 1: Predicted illusion strength ratings for expanding and rotating motion illusions. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals.

2.2.1.2 Cybersickness

Discomfort ratings were predicted using a linear mixed effect model including illusion type (expanding vs. rotating) as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiments looks as followed:

$$Model = lmer\ (Discomfort\ Rating \sim Illusion\ Type + (1|Observer))$$

Test statistics as well as descriptive statistics for the models for general discomfort, headache, blurred vision, dizziness and eye strain ratings can be found in Table 1. Observers experienced significantly more general discomfort and blurred vision for rotating illusions compared to expanding illusions. However, no differences in headache, dizziness or eye strain ratings were found for the illusion types.

2.2.1.3 Head movements

Head movements in medio – lateral and anterior – posterior directions were predicted using linear mixed effect models, including illusion type (rotating vs. expanding) 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 for this and all the following analyses. Following this transformation, no deviation from homoscedasticity or normality was observed. The function of the model for this and the following experiments looks as followed:

Model= lmer (log (Head movements) ~ Illusion Type+ (1|Observer))

No significant effect of illusion type was found for head movements in the medio – lateral direction (F(1,369.06) = 0.50, p = .481) or the anterior-posterior direction (F(1,369.05) = 0.04, p = .833).

2.2.2 Medio-lateral vs anterior-posterior head movements

Head movements were predicted using linear mixed effect models, including direction of head movements (medio-lateral vs. anterior-posterior) as fixed effects and the intercept for observers as random effect. The function of the model for this and the following experiments looks as followed:

Model= lmer (log (Head movements) ~ Direction+ (1|Observer))

Direction of head movements had a significant effect on the magnitude of head movements (F(1, 768)= 444.08 , p <.001 , f^2 = .58, ΔBIC = 344.22), with more head movements in the anterior-posterior (M = -3.22, SD = 0.40) direction compared to the medio-lateral direction (M = - 3.78, SD = 0.61), see Figure 3.

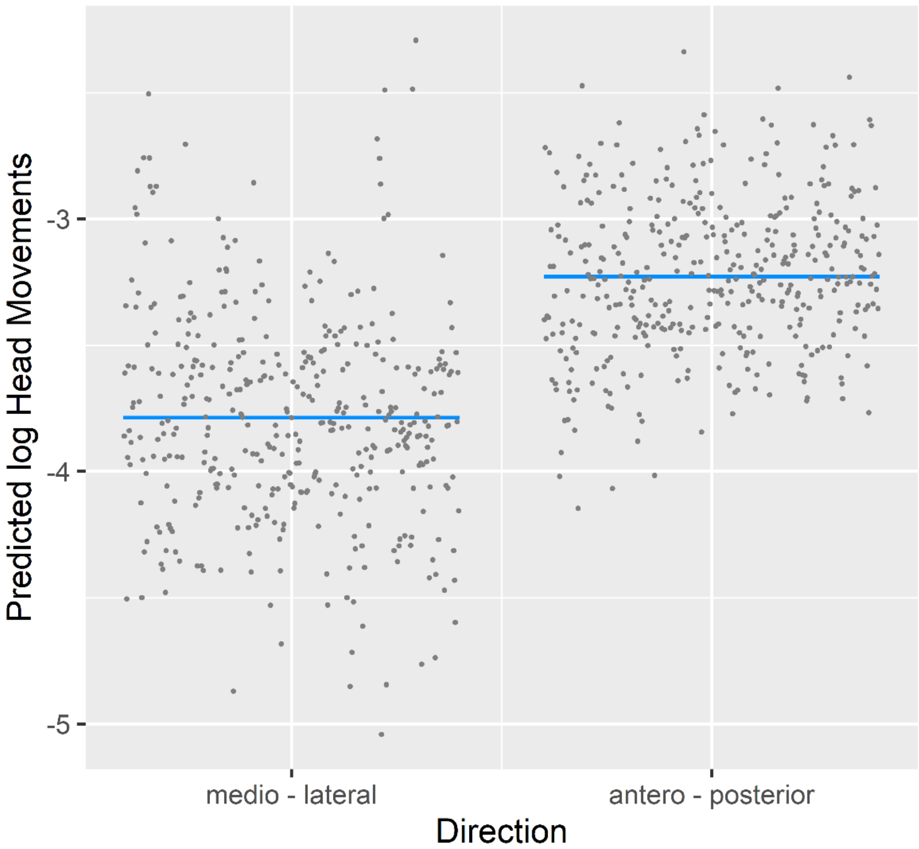

Figure 3: Experiment 1: Predicted head movements in medio-lateral and anterior-posterior direction. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals.

2.2.3 Effect of Illusion Strength on Discomfort and Head movements

2.2.3.1 Cybersickness

Discomfort ratings were predicted using a linear mixed effect model including illusion strength as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiments looks as followed:

Model = lmer (Discomfort Ratings ~ Illusion Strength + (1|Observer))

Test statistics as well as descriptive statistics for the models for general discomfort, headache, blurred vision, dizziness and eye strain ratings can be found in Table 1. General discomfort, dizziness and eye strain ratings increased significantly with increasing illusion strength, whereas blurred vision and headache ratings were not significantly affected by illusion strength. Models are displayed in Figure 4.

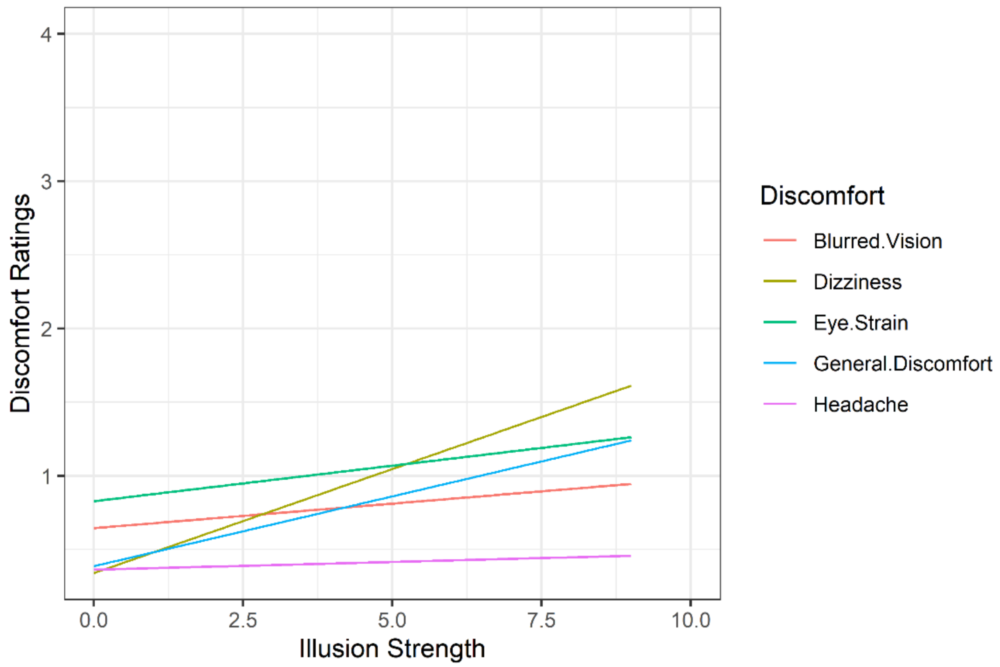

Figure 4: Experiment 1: Predicted illusion strength ratings by discomfort ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

2.2.3.2 Head movements

Head movements were predicted using a linear mixed effect model including illusion strength as fixed effect and intercept for observer as random effects. The function of the model looks as followed:

$$Model = lmer\ (log(Head\ movements) \sim Illusion\ Strength + (1|Observer))$$

No significant effect of illusion strength on medio - lateral head movements ($F(1, 392.19)= 0.33$, $p= .566$) or anterior-posterior head movements ($F(1, 393.33)= 0.15$, $p= .700$) was found.

2.2.4 Relationship between cybersickness and head movements

Head movements were predicted using a linear mixed effect model including general discomfort, headache, blurred vision, dizziness and eye strain as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiments looks as followed:

$$Model = lmer\ (log(Head\ movements) \sim General\ Discomfort + Headache + Blurred\ Vision + Dizziness + Eye\ Strain + (1|Observer))$$

No significant effect of general discomfort ($F(1,383.62)= 1.20$, $p =.274$), headache ($F(1,386.79)= 0.19$, $p =.662$), blurred vision ($F(1,378.45)= 1.42$, $p =.235$), dizziness ($F(1,385.73)=1.59$, $p =.208$) or eye strain ratings ($F(1,390.73)= 2.53$, $p =.113$) on medio-lateral head movements was found. A significant effect of dizziness ratings on anterior- posterior head movements was found, $F(1,385.97)= 6.91$, $p = .009$, $f^2 = .05$, $\Delta BIC = 0.87$, with head movements increasing by 0.04m (± 0.01m) with each increase in dizziness, see Figure 5. No significant effect of general discomfort ($F(1, 383.83)= 0.0001$, $p =.992$), headache ($F(1, 387.03)= 2.10$, $p =.148$), blurred vision ($F(1,378.57)= 1.45$, $p =.230$) or eye strain ratings ($F(1,390.94)= 0.89$, $p =.347$) on anterior-posterior head movements was found.

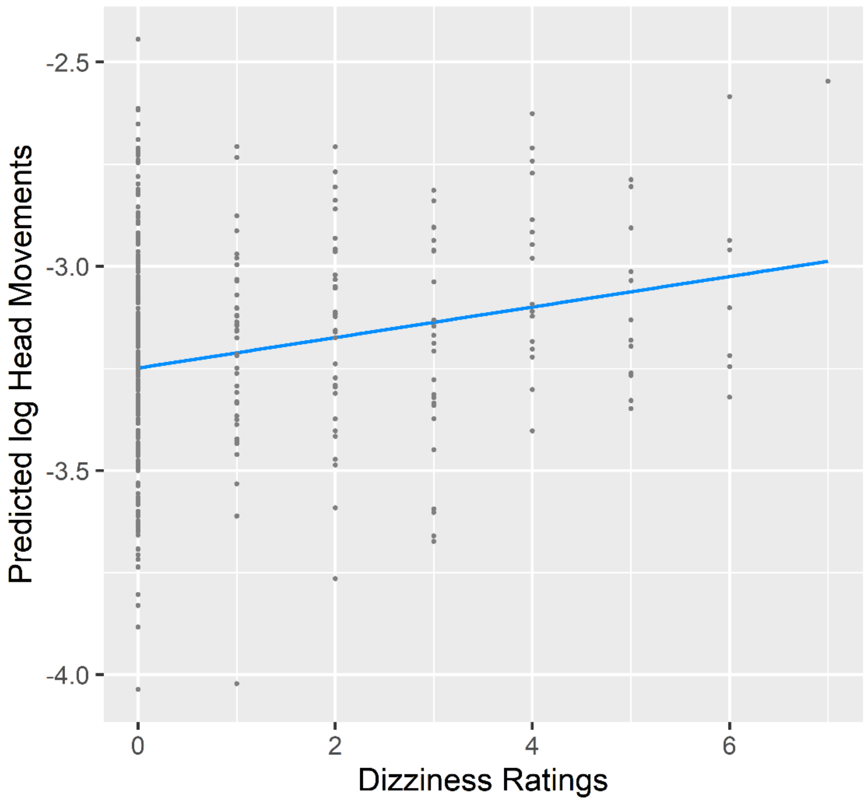

Figure 5: Experiment 1: Predicted head movements in the anterior-posterior direction by dizziness ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals.

2.3 Discussion

Expanding motion illusions elicit the illusion of motion-in-depth and were therefore expected to cause more discomfort in the observer [13,89–91]. Contrary to predictions, rotating motion illusion were rated higher on three of the discomfort scales (general discomfort, blurred vision and eye strain) compared to expanding motion illusions. However, given that the BIC values were negative, this result should be interpreted with caution, as this suggests the evidence is not strong for a difference in experienced discomfort between the motion directions. As observers saw more movement in the rotating motion illusions compared to the expanding ones, the stronger perceived movement in these illusions might have influenced the subjective experience of discomfort. However, there was no difference in head movements for expanding or rotating illusions. To further understand the relationship between head movements and experienced discomfort illusory self-motion (vection) was recorded in Experiment 2.

3 Experiment 2

Vection shows a complex relationship with postural instability, therefore it was expected that illusions causing stronger vection in an observer would also lead to more head movements, particularly in the anterior-posterior direction. However, postural instability can also be affected by visual motion stimulation independent of vection [92]. Postural control mechanisms are believed to be based on both automatic preconscious processing of visual motion as well as the conscious processing of an optic flow stimulus. Postural sway caused purely by visual motion is preconscious whereas postural sway caused by vection is a more conscious process [92,93]. Postural sway caused by visual motion itself will be represented in the relationship between head movements and illusion strength ratings and postural sway caused by vection will be represented in the relationship between vection magnitude ratings and head movements. Stimulus duration affects vection magnitude with longer duration increasing the experience of vection which was cause for an increase in presentation time in this experiment, presenting the illusions for 90s rather than 30s as in Experiment 1. Only expanding motion illusions were presented in this experiment to initially test their ability to induce vection in the observer. In Experiment 3 both rotating and expanding motion illusions will be presented allowing a comparison of the effects they have on vection.

3.1 Methods

3.1.1 Observers

Forty-five observers took part in the study (age range between 19 – 21 years, M = 19.8 years, SD = 0.73) with normal or corrected to normal vision.

3.1.2 Apparatus

The same set up as in Experiment 1 was used.

3.1.3 Stimuli

Six expanding motion illusions out of the 14 illusions from the first experiment were chosen as stimuli for this study, for example see Figure 1c and 1d. Stimuli contained 3 low spatial frequency images and 3 high spatial frequency images. Observers again determined optimal distance for each illusion resulting in the images taking up between 5.72° and 41.11° of the visual field (M = 13.77°, SD = 5.82°). Expanding motion illusions were selected for this experiment to investigate their effect on the perception of linear vection rather than investigating circular vection elicited by rotating illusions.

3.1.4 Measures

The same measures as in experiment one were recorded. Additionally, observers also verbally rated their experienced vection magnitude on the 11-point Likert scale and initiated vection onset times by button press.

3.1.5 Procedure

Procedure in Experiment 2 was identical to Experiment 1 with the addition of observers rating experienced vection magnitude after each stimulus presentation, observers indicating the onset of vection by button press, and stimuli being presented for 90 seconds instead of 30 seconds in the second part of the experiment. This longer presentation time was chosen as longer exposure to an environment that is perceived as moving increases the chances of vection and cybersickness being experienced by the observers.

3.1.6 Analysis

Data analysis was identical to the method used in experiment 1.

3.2 Results

3.2.1 Medio-lateral vs anterior-posterior head movements

The direction of head movements had a significant effect on the magnitude of head movements ($F(1, 472)= 56.42$, $p <.001$, $f^2 = .12$, $\Delta BIC = 47.16$), with more head movements in the anterior-posterior ($M = - 2.79$, $SD = 0.44$) direction compared to the medio-lateral direction ($M = - 3.08$, $SD = 0.72$).

3.2.2 Effect of illusion strength on discomfort, vection and head movements

3.2.2.1 Cybersickness

Test statistics as well as descriptive statistics for the models for general discomfort, headache, blurred vision, dizziness and eye strain ratings can be found in Table 2. Models are displayed in Figure 6. Illusion strength significantly affected all cybersickness measures (general discomfort, blurred vision, dizziness, eyes train) but headache, with stronger adverse symptoms being experienced for illusions that were perceived as moving more.

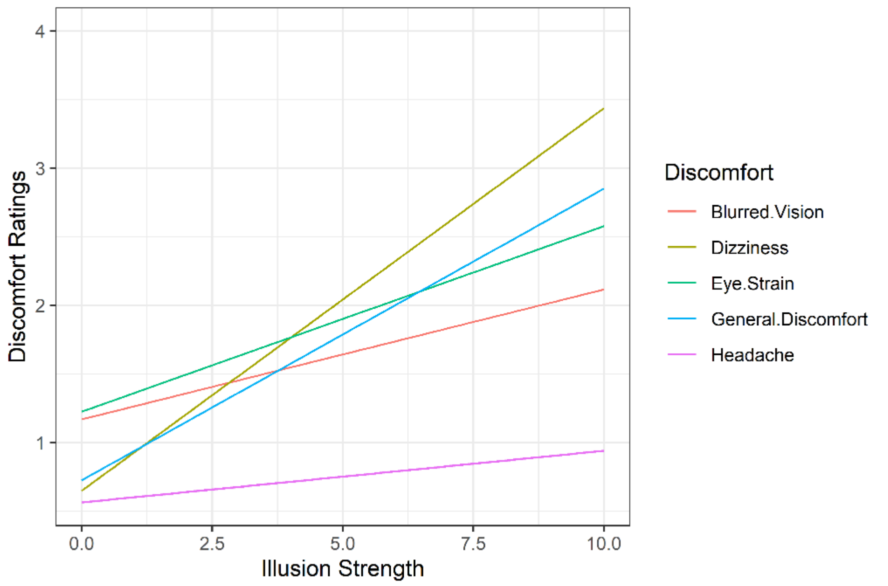

Figure 6: Experiment 2: Predicted illusion strength ratings by discomfort ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

3.2.2.2 Vection

Vection measures were predicted using a linear mixed effect model including illusion strength as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiment looks as followed:

$$Model = lmer\ (Vection\ Measure \sim Illusion\ Strength + (1|Observer))$$

There was a significant effect of illusion strength on vection magnitude ratings (F (1, 497.33) = 497.62, p <.001, f^2 = .98, ΔBIC = 340.73), with vection magnitude increasing by 0.65 (± 0.03) with each increase in illusion strength rating, see Figure 7. No significant effect of illusion strength on vection onset times was found, F (1, 318.96) = 1.13, p =.289.

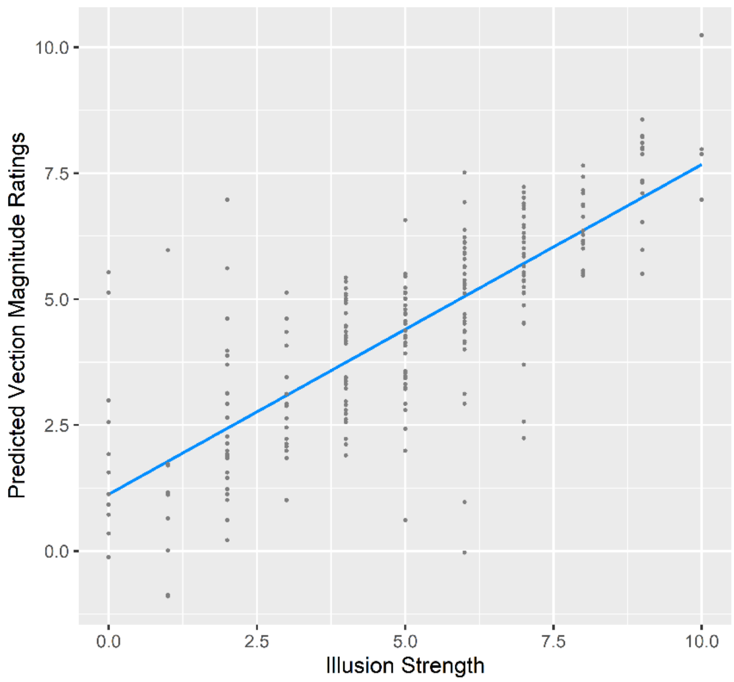

Figure 7: Experiment 2: Predicted vection magnitude ratings based on illusion strength. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals.

3.2.2.3 Head movements

No significant effect of illusion strength on head movements in the medio-lateral ($F(1,237.34)= 0.03$, $p= .855$) or anterior-posterior direction ($F(1,245.63)= 0.01$, $p= .924$) was found.

3.2.3 Relationship of cybersickness, vection and head movements

3.2.3.1 Relationship between vection measures and cybersickness

Discomfort measures were predicted using a linear mixed effect model including vection magnitude and vection onset as fixed effects and intercept for observer as random effect. The function of the model for this and the following experiment looks as followed:

$$Model = lmer\ (Discomfort\ Ratings \sim Vection\ Magnitude + Vection\ Onset + (1|Observer))$$

Test statistics as well as descriptive statistics for the models for general discomfort, headache, blurred vision, dizziness and eye strain ratings can be found in Table 3. Vection magnitude ratings significantly affected all the cybersickness measures, with illusions eliciting a stronger sensation of vection also leading to a stronger sensation of adverse symptoms. Vection onset times only significantly affected blurred vision ratings, with shorter vection onset times being experienced for stimuli eliciting a stronger sensation of blurred vision. Significant vection magnitude models are displayed in Figure 8.

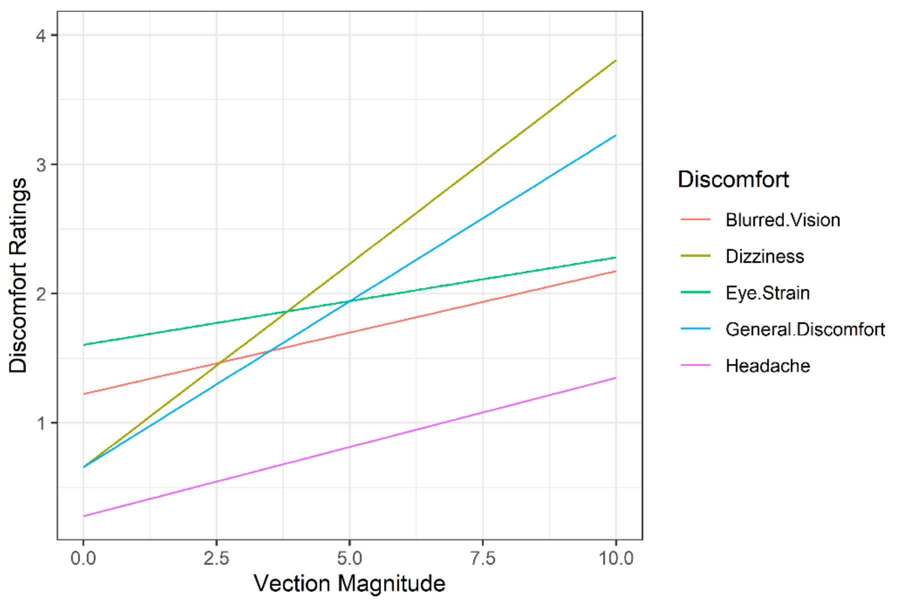

Figure 8: Experiment 2: Predicted discomfort ratings based on vection magnitude ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

3.2.3.2 Relationship between cybersickness and head movements

No significant effect of general discomfort ($F(1,241.36) = 1.14$, $p = .286$), headache ($F(1,250.14) = 1.70$, $p = .193$), blurred vision ($F(1,251.99) = 1.31$, $p = .253$), dizziness ($F(1,251.91) = 0.11$, $p = .742$), or eye strain ($F(1,244.29) = 1.07$, $p = .303$) on medio-lateral head movements was found. Similarly, no significant effect of general discomfort ($F(1,248.26) = 0.22$, $p = .637$), headache ($F(1,251.72) = 0.15$, p

=.698), blurred vision (F(1,247.13)= 0.44, p =.508), dizziness (F(1,248.27)= 0.04, p =.839), or eye strain (F(1,250.39)= 0.51, p =.478) on anterior-posterior head movements was found.

Relationship between vection measures and head movements

Head movements were predicted using a linear mixed effect model including vection magnitude and vection onset as fixed effect and intercept for observer as random effect. The function of the model for this and the following experiment looks as followed:

$$Model = lmer\ (log(Head\ movement) \sim Vection\ Magnitude + Vection\ Onset + (1|Observer))$$

No significant effect of vection magnitude (F(1,156.56)= 2.22, p =.139) or vection onset (F(1,152.2)= 0.19, p =.660) on medio-lateral head movements was found. Similarly, no significant effect of vection magnitude (F(1,157.78)= 0.13, p =.721) or vection onset times(F(1,154.43)= 0.24, p =.627) was found on anterior-posterior head movements.

3.3 Discussion

As predicted, stronger motion illusions elicited stronger vection magnitude in the observers. Vection magnitude showed a positive relationship to all measures of discomfort; however, vection onset had no effect on discomfort ratings, suggesting that perceived motion is sufficient to elicit vection. There is no relationship between discomfort and head-movements. There was also no relationship between vection magnitude and head-movements (although in both cases head-movements only refers to positional variability). There was no relationship between either discomfort or vection and head movements. The experiment also showed a relationship between discomfort and vection. Illusion strength varied between the stimuli, and as these are artworks, the stimuli differ in several ways, e.g. colour content, exact spatial frequencies included, etc. Experiment 3 used controlled stimuli and attempts were made to match rotating and expanding stimuli for illusion strength. Spatial frequency of the stimuli has been shown to affect illusion strength ratings in Experiment 1 and 2, some of the cybersickness measures (Experiment 1: eye strain; Experiment 2: general discomfort, dizziness and eye strain) as well as vection magnitude and vection onset times (see Supplementary Material 3), with low spatial frequency stimuli in general being perceived as moving more, causing more discomfort and vection.

4 Experiment 3

Experiment 1 and 2 have shown that spatial frequency affects the strength of illusory motion perceived in the images (see Supplementary Material 3). In this experiment, 5 controlled grey scaled illusions ranging from high to low spatial frequency were designed for each motion direction. Additionally, the 10 illusions were judged for illusion strength in a 2-alternative forced choice task (see Supplementary Material 4 for details). As spatial frequency has been shown to affect illusion strength it was varied in an attempt to create rotating and expanding illusions of equal illusion strength.

4.1 Methods

4.1.1 Observer

Seventy-six observers with normal or corrected to normal vision took part in the study. A larger sample size was chosen for this experiment due to a weaker motion signal being expected by controlled motion illusions. Due to technical problems the data of 5 were not recorded correctly resulting in a final sample size of 71 observers ranging from 18 to 39 years (M= 20.55 years, SD=3.42).

4.1.2 Apparatus

The same set up as in the experiment 1 and 2 was used with the exception of the headset. 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. It has a refresh rate of 120Hz and depending on observer settings yields a FOV of up to 130°. This headset was chosen over the previously used one as the resolution was improved which is believed to enhance the illusion.

4.1.3 Stimuli

The stimuli used in this study consisted of 4 circular optimized Fraser Wilcox illusions, with each made up by 8 rings containing patterns with gradient luminance profiles (black to dark grey and white to light grey), see Figure 9. The illusions were created based on the prior conducted two alternative forced choice (2AFC) task in which 5 rotating and 5 expanding motion illusions, which varied in spatial frequency were matched for illusion strength. The 3 weakest rated rotating illusions as well as the 3 highest rated expanding motion illusions were selected and for each group 3 more illusions similar in spatial frequency were created. Resulting in 6 expanding motion illusion in the mid-range of spatial frequency and 6 rotating motion illusions 2 of them being low in spatial frequency and 4 being high in spatial frequency. These stimuli were created to result in rotating and expanding motion illusions that are similar in illusion strength (for figures see Supplementary Material Resources 5a). The illusion covered 23° of the visual field.

a b

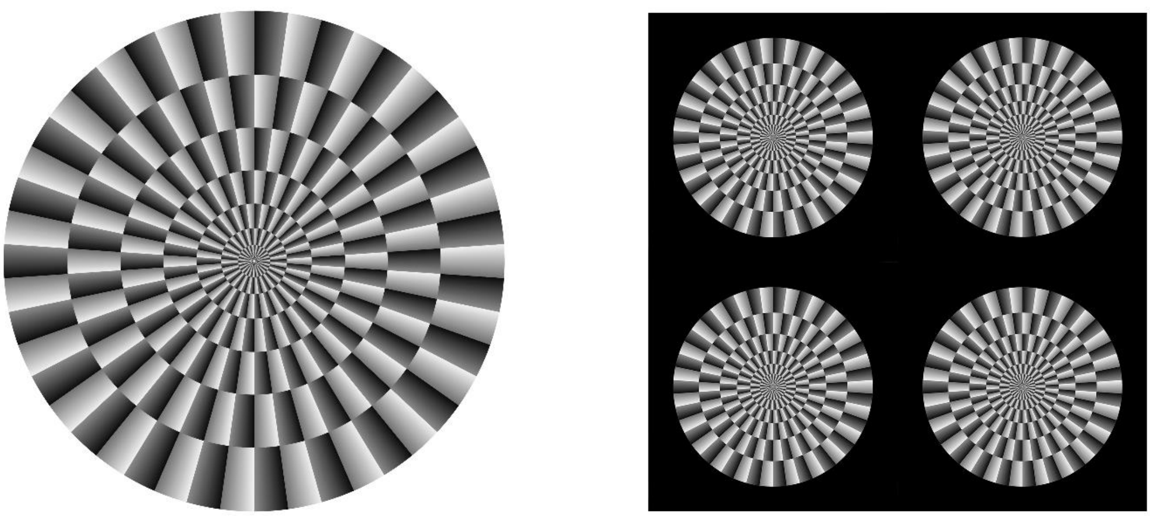

Figure 9: Example of a rotating motion illusion (a) and the corresponding stimulus (b). used in Experiment 3. Stimuli were based on the optimised illusions but matched for colour (all grey-scale) and spatial frequency content. Stimuli were also matched for perceived illusion strength, based on the 2AFC pilot study.

4.1.4 Measures

The same measures for discomfort (general discomfort, headache blurred vision, dizziness, eye strain ratings), vection (magnitude ratings, onset times) and head movements (medio-lateral and anterior-posterior displacement) as in Experiment 2 were recorded. Additionally, vection duration was recorded indicated by button press and button release. Vection onset and duration times were again included as measures in this experiment even though no relationship was found in Experiment 2 as previous research has found a correlation between increased vection strength, shorter vection onset times and longer vection duration [31,94].

4.1.5 Procedure

The procedure was similar than in Experiments 1 and 2. The experiment consisted of two parts: a training and the experimental trial. Twelve motion illusions were presented in random order. In the training trial, the illusions were presented one after the other for 5 seconds. In this short training observers were able to practise pressing the trigger button when they experienced vection in the trials, got familiar with the type of stimuli that were going to be presented in the experimental trial and they familiarised themselves with the procedures. In the experimental trial illusions were presented for 90 seconds. While viewing the illusions observers were instructed to indicate when they started experiencing vection (vection onset) by pressing a button and to hold it in for as long as the experience of vection lasted (vection duration). They were able to press the button multiple times per trial. After each stimulus presentation, observers verbally rated the illusion on 11-point Likert scale.

4.1.6 Analysis

Data analysis was identical to the method used in experiment 1 and 2.

4.2 Results

4.2.1 Expanding vs Rotating illusions

4.2.1.1 Illusion strength

A significant effect of illusion type on illusion strength ratings was found, $F(1,1632)=30.17$, $p<.001$, $f^2 = .02$, $\Delta BIC = 22.5$. Rotating motion illusions were rated significantly higher on illusion strength (M = 3.40, SD= 2.27) compared to expanding motion illusions (M = 2.90, SD = 2.26), suggesting that observers perceived more movements in rotating motion illusions (for figures see Supplementary Material 5b).

4.2.1.2 Cybersickness

Test statistics as well as descriptive statistics for the models for general discomfort, headache, blurred vision, dizziness and eye strain ratings can be found in Table 4. Observers experienced significantly more eye strain for rotating compared to expanding illusions. None of the other cybersickness measures differed significantly between the two illusion types.

4.2.1.3 Vection

A significant effect of illusion type on vection magnitude ratings was found, $F(1,1632)=4.93$, $p= .027$, $f^2 = .003$, $\Delta BIC = - 2.6$. Rotating motion illusions were rated significantly higher on vection magnitude (M = 2.37, SD= 2.51) compared to expanding motion illusions (M = 2.17, SD = 2.43), suggesting that observers felt more self-motion for rotating motion illusions, see Figure 10. No significant effect of illusion type on vection onset times was found, $F(1,950.67)= 3.64$, $p= .0568$. Vection was experienced similarly fast after stimulus onset for rotating (M = 24.91s, SD= 21.69s) compared to expanding motion illusions (M = 26.77s, SD = 22.61s). Similarly, no significant effect of illusion type on vection duration times was found, $F(1,946.59)= 0.86$, $p= .353$. Vection was experienced for the same amount of time for rotating (M = 17.61s, SD= 20.84s) and expanding motion illusions (M = 17.16s, SD = 20.93s).

Figure 10: Experiment 3: Predicted vection magnitude ratings for expanding and rotating motion illusions. 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.

4.2.1.4 Head movements

No significant effect of illusion type was found for head movements in the medio – lateral direction (F(1,834.01) = 0.04, p = .847) or the anterior-posterior direction (F(1,834.01) = 0.28, p = .595). Direction of head movements had a significant effect on the magnitude of head movements (F(1, 1632)= 323.17, p <.001 , f^2 = .20, ΔBIC = 287.6), with more head movements in the anterior-posterior (M = - 2.79, SD = 0.37) direction compared to the medio-lateral direction (M = - 3.13, SD = 0.70).

4.2.3 Effects of Illusion strength on discomfort, vection and head movements

4.2.3.1 Cybersickness

Test statistics as well as descriptive statistics for the models for general discomfort, headache, blurred vision, dizziness and eye strain ratings can be found in Table 4. A significant relationship of illusion strength for all cybersickness measures was found. The models are displayed in Figure 11.

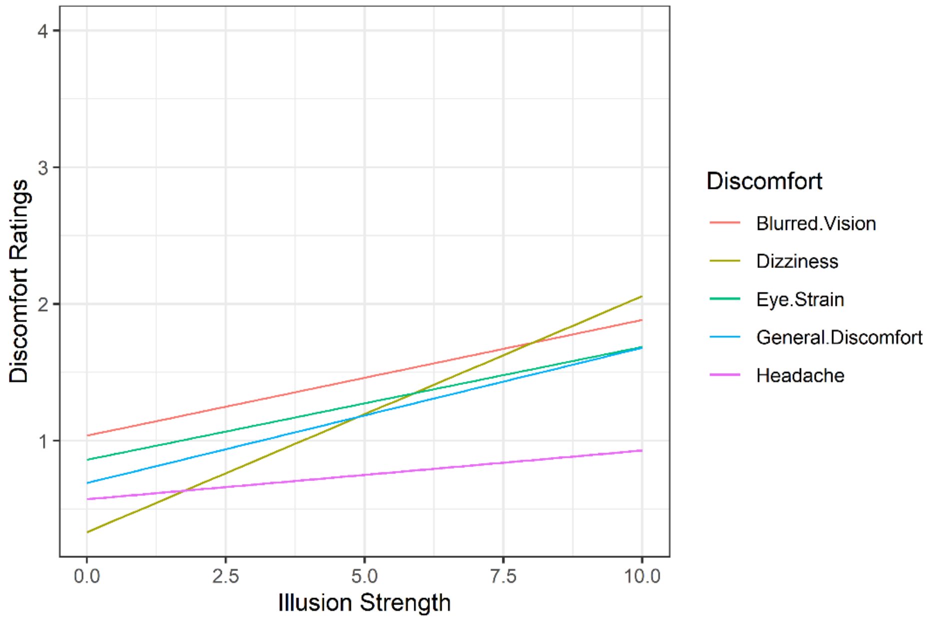

Figure 11: Experiment 3: Predicted illusion strength ratings by discomfort ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

4.2.3.2 Vection

There was a significant effect of illusion strength on vection magnitude ratings ($F(1, 1687.7) = 773.08$, $p <.001$, $f^2 = .34$, $\Delta BIC = 630.6$), with vection magnitude increasing by 0.54 (± 0.02) with each increase in illusion strength rating, see Figure 12a. Similarly, a significant effect of illusion strength on vection onset times ($F(1, 998.79) = 25.18$, $p <.001$, $f^2 = .01$, $\Delta BIC = 18$) was found, with vection onset times decreasing by 1.56s (± 0.31) with each increase in illusion strength rating, see Figure 12b. There was also a significant effect of illusion strength on vection duration times ($F(1, 963.78) = 169.14$, $p <.001$, $f^2 = .14$, $\Delta BIC = 149.5$), with vection duration increasing by 2.09 (± 0.16) with each increase in illusion strength rating, see Figure 12c.

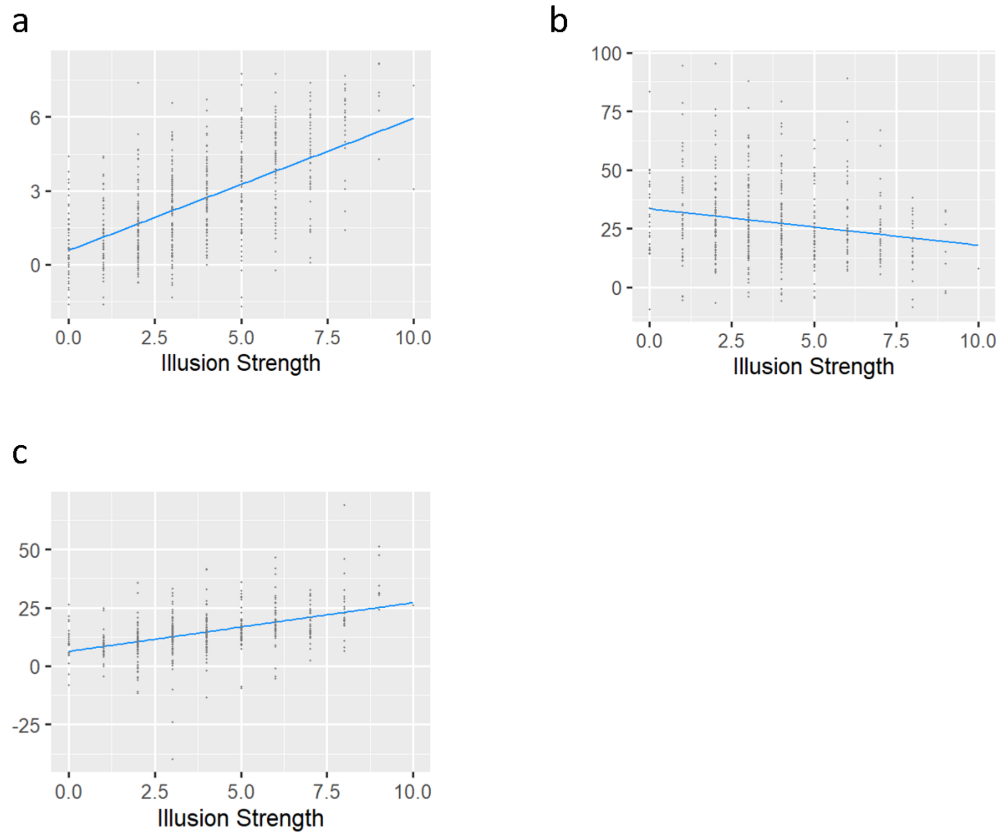

Figure 12: Experiment 3: Predicted a) vection magnitude ratings, b) vection onset times (s) and c) vection duration times (s) based on illusion strength. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals.

4.2.3.3 Head movements

No significant effect of illusion strength on head movements in the medio-lateral ($F(1,855.71)= 3.50$, $p = .062$) or anterior-posterior direction ($F(1,858.46)= 1.58$, $p = .210$) was found.

4.2.4 Relationship between cybersickness, vection and head movements

4.2.4.1 Relationship between vection measures and cybersickness

Test statistics as well as descriptive statistics for the models for general discomfort, headache, blurred vision, dizziness and eye strain ratings can be found in Table 5. Vection magnitude showed a significant relationship with general discomfort, blurred vision, dizziness and eyestrain. However, no significant relationship between vection magnitude and headache ratings was found. No relationship between cybersickness measures and vection onset or duration times were found. Models are displayed in Figure 13.

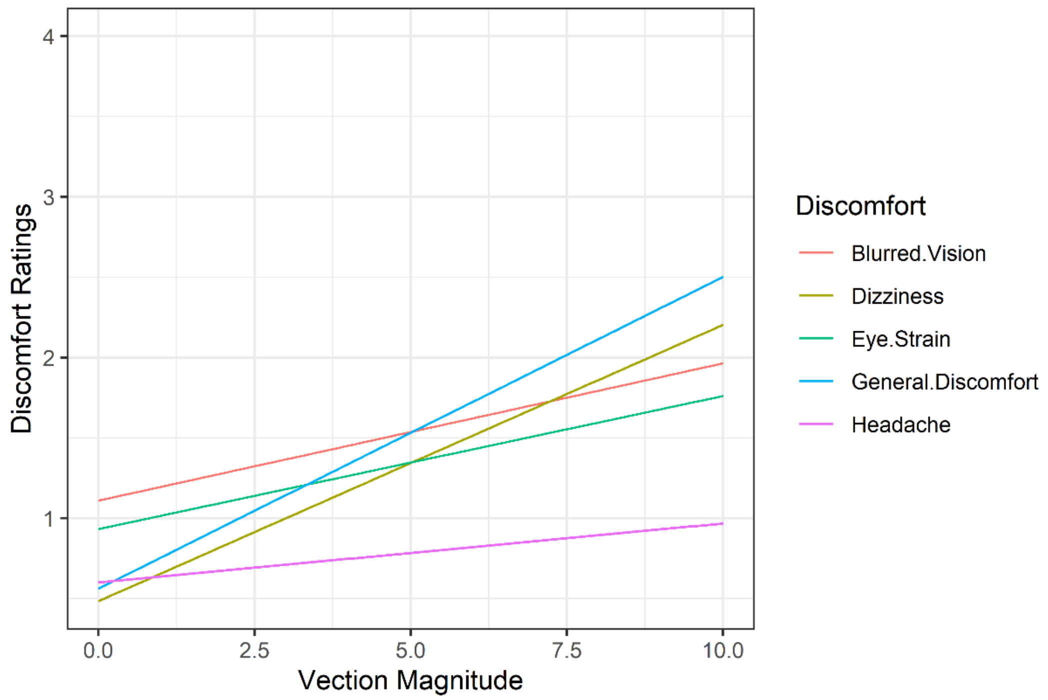

Figure 13: Experiment 3: Predicted discomfort ratings based on vection magnitude ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

4.2.4.2 Relationship between cybersickness and head movements

A significant effect of dizziness ratings on medio-lateral head movements was found, $F(1,816.57)= 5.70$, $p = .017$, $f^2 = .003$, $\Delta BIC = -1.00$, with head movements increasing by 0.03m (± 0.01m) with each increase in dizziness. No significant effect of general discomfort ($F(1, 821.44)= 0.86$, $p =.354$), headache ($F(1,806.05)= 2.98$, $p = .085$), blurred vision ($F(1,833.03)= 0.04$, $p =.085$) or eye strain ratings ($F(1,831.31)= 0.29$, $p =.590$) on head movements in the medio-lateral direction was found.

Similarly, a significant effect of dizziness ratings on head movements in the anterior-posterior direction was found ($F(1,828.67)= 4.04$, $p = .045$, $f^2 = -0.004$, $\Delta BIC = -2.68$), with head movements increasing by 0.01m (± 0.007m) with each increase in dizziness. A significant effect of eye strain ratings on head movements was found, $F(1,842.02)= 5.45$, $p = .020$, $f^2 = .03$, $\Delta BIC = -1.32$, with head movements increasing by 0.02m (± 0.008m) with each increase in eye strain. No significant effect of general discomfort ($F(1,833.79)= 2.56$, $p =.110$), headache ($F(1,816.45)= 0.30$, $p =.587$) or blurred vision ratings ($F(1,843.30)= 0.37$, $p =.543$) on head movements was found (for figures see Supplementary Material 5c).

4.2.4.3 Relationship between vection measures on head movements

No significant effect of vection magnitude ($F(1,486.03)= 1.70$, $p =.192$), vection onset ($F(1,476.67)= 2.04$, $p =.154$) or vection duration ($F(1,473.49)= 0.13$, $p =.718$) on medio-lateral head movements was found. However, vection magnitude ratings had a significant effect on anterior-posterior head movements, $F(1,490.2)= 10.57$, $p = .001$, $f^2 = -0.01$, $\Delta BIC = 4.33$, with head movements increasing by 0.02m (± 0.01m) with each increase in vection magnitude, see Figure 14. No significant effect of vection onset ($F(1{,}480.8) = 0.28$, $p = .560$) or vection duration ($F(1{,}452.7) = 0.36$, $p = .548$) on head movements was found.

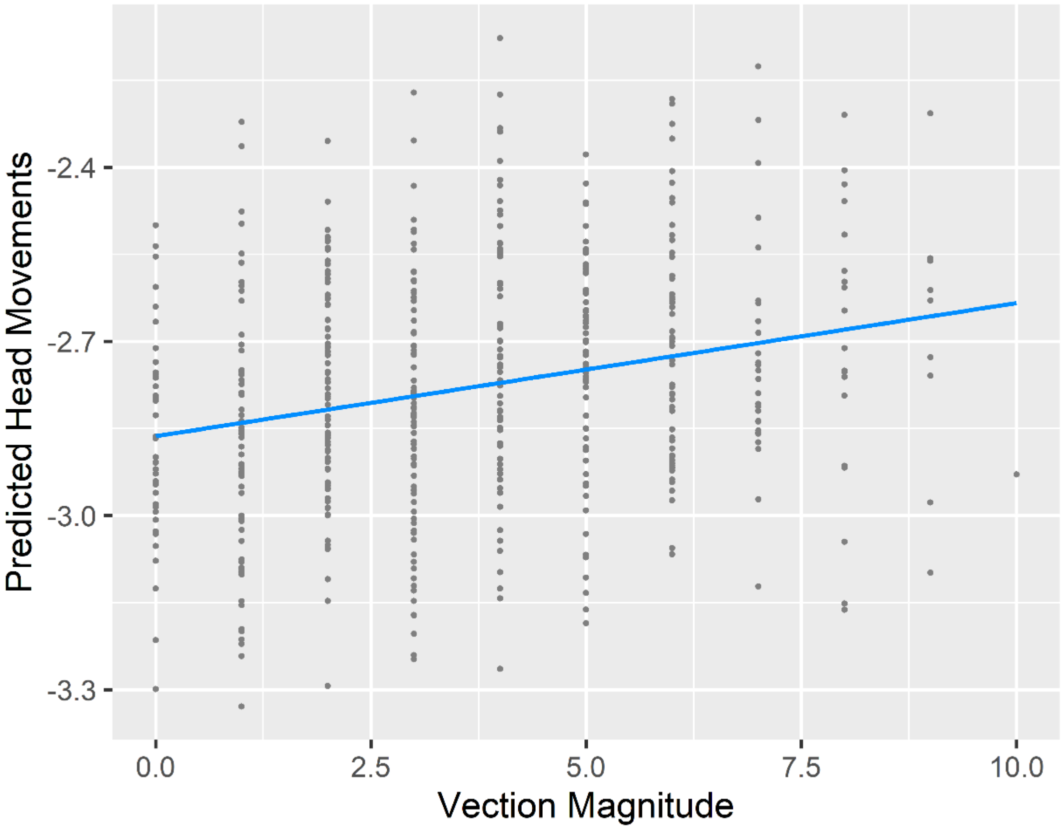

Figure 14: Experiment 3: Predicted head movements in the anterior-posterior direction by vection magnitude. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. Lines representing model fits and points representing residuals.

4.3 Discussion

Rotating illusions were again rated higher for illusion strength compared to expanding illusions, despite attempts to match them for illusion strength. Only eye strain ratings were affected by illusion type, while none of the other discomfort measures were affected. Rotating illusions elicited a stronger experience of vection compared to expanding illusions.

As expected, greater illusion strength elicited more discomfort and vection. However, illusion strength had no effect on head movements. As these grey-scaled stimuli are weaker overall compared to the optimised illusions in the artwork the motion signal elicited might not be strong enough to elicit head movements. Illusions that caused more vection also elicited more general discomfort, blurred vision, dizziness and eye strain. Head movements in both directions are related to dizziness ratings and head movements in the anterior-posterior direction are related to experienced vection. Dizziness is also the discomfort measure that is most affected by the experience of vection suggesting that dizziness might be the component of discomfort that links vection, discomfort and sway.

5 General Discussion

The three presented experiments aimed to investigate the relationship of cybersickness, vection and head movements experienced in a virtual environment using HMDs. Optimised Fraser Wilcox illusions were presented to observers to investigate the role of the conflict between the visual and vestibular independently of the conflict between accommodation and vergence. It was predicted that there would be an effect of motion direction of the perceived motion (rotating vs. expanding) as well as an effect of illusion strength, on cybersickness, vection and head movements

5.1 Summary of Results

The results showed that the strength of the perceived illusion had an effect on vection and cybersickness (Experiments 1, 2, 3). The greater the illusion strength (the more it was perceived as moving) the more discomfort and vection the observer experienced. This shows that perceived motion alone and no explicit real motion is necessary to perceive illusory self-motion in a virtual reality environment.

The experiments also revealed a relationship between vection magnitude and several of the discomfort measures. Illusions that caused stronger vection also caused more severe adverse symptoms in the observer. However, vection onset (Experiments 2, 3) and duration (Experiment 3) did not relate to discomfort ratings. Vection magnitude was also related to head movements in the anterior -posterior direction in Experiment 3. Finally, dizziness was found to be the measure of cybersickness that primarily related to head movements. It was related to anterior-posterior head movements in Experiments 1 and 3 as well as to medio-lateral head movements in Experiment 3.

Overall, more head movements in the anterior-posterior direction compared to the medio-lateral direction were found independent of motion direction of the presented illusions. However, illusion strength had no effect on head movements in either the anterior-posterior or medio-lateral direction.

Rotating illusions were rated higher for illusion strength compared to expanding motion illusions (Experiments 1, 3), irrespective of colour, spatial frequency or contrast of the presented illusions. Rotating illusions were also rated higher on vection magnitude as well as for some discomfort measures (Experiments 2, 3). Again, illusion type had no effect on head movements in either direction (Experiments 1, 3).

5.2 Dominance of Rotating Motion Illusions

One unexpected finding here was the dominance of rotating motion illusions over expanding motion illusions. A possible explanation could be that stereoscopic cues undermine the illusory motion for expanding motion illusions as they indicate no change in the depth plane. There are several cues to motion-in-depth including stereoscopic [95–97] and looming cues [95,98]. Stereoscopic cues are more relevant for the perception of motion-in-depth compared to lateral motion, and the stereoscopic cues would indicate no motion, resulting in a weaker perception of expanding illusions specifically. This is likely as prior research investigating rotating motion illusions (rotating snake) has found that the illusory motion is more pronounced for binocular compared to monocular viewing [35,39].

Rotating motion illusion also resulted in more discomfort and stronger vection compared to expanding illusions (Experiment 1, 3). Previous research has shown more adverse symptoms for stimuli moving in depth compared to laterally moving stimuli [13,89]. However, the results in the current study should be interpreted with caution as the BIC values for the models are in favour of the null model, suggesting little evidence for an effect of motion direction on cybersickness. Rotating illusions were also rated higher for vection magnitude compared to expanding motion illusions (Experiment 2, 3); however, the BIC values again indicate weak evidence.

5.3. Illusion Strength as Predictor of Cybersickness and Vection

By contrast, illusion strength has been found to affect the experience of discomfort in all three experiments (Experiment 1: general discomfort, dizziness and eye strain; Experiment 2: general discomfort, blurred vision, dizziness and eye strain; Experiment 3: general discomfort, headache, blurred vision, dizziness and eye strain), with BIC values generally strongly in favour of the full model. Based on these results it seems that rather than motion direction, illusion strength is important factor in inducing discomfort. Similarly, as for cybersickness ratings, illusion strength seems to be driving stronger experiences of vection rather than motion direction. Illusion strength significantly affected the experience of vection magnitude with BIC and f^2 values suggesting strong effects. Vection onset times and duration times, however, were not affected by either illusion type or illusion strength. This suggests that the perceived illusory motion affected vection strength but not timing.

Illusion strength (strength of perceived motion) rather than illusion type (motion direction) affected both the experience of cybersickness and vection in all experiments. 2D motion illusions were used so that the accommodation-vergence conflict was held constant, this will minimise the discomfort from the visual system alone. As both cybersickness and vection increased with stronger perceived motion, this would suggest that the sensory conflict perceived might be the primary cause of both phenomena, when the effects of accommodation-vergence conflict are minimised.

Allowing observers to play a first-person Spiderman game prior to the experiment could have affected their susceptibility to cybersickness and vection for the following motion illusions. In future research cybersickness severity should be assessed before and after such introductory VR games to directly measure their effects on observers cybersickness levels. However, this gameplay was present for all observers at the beginning of the experiment, and so any effect on the later experience of vection would have been the case for all stimuli. The experience of cybersickness was strongly affected by perceived illusion strength in all experiments, with illusions that were perceived as moving more also eliciting a stronger sensation of cybersickness. Similarly, illusions that were perceived as moving more also elicited a stronger sensation of vection.

It has been shown that the experience of vection can be highly affected by an observer's cognitive bias [99–101]. Therefore, informing observers prior to the experience that the presented stimuli could induce vection might have biased their perception of vection in the current experiments. If this was the case the reported vection in the current experiments would reflect demand characteristics rather than a real perception of vection. However, if cognitive bias alone is responsible for the experience of vection we would expect all illusions to elicit a similar sensation of vection independent of the strength of illusory motion perceived in them. In all experiments reported here vection magnitude was strongly affected by illusion strength, which would suggest that vection in the current study is at least partially affected by the motion perceived in the illusions. Additionally, if the experience of vection was solely due to demand characteristics the responses in the 2AFC pilot (see Supplementary Material 4) should have worked out at chance with all illusions being picked as the "stronger one" in around half of the trials. However, the findings showed a clear dominance of rotating illusions as well as an effect of spatial frequency on the response choices. Some observers also did not experience any vection for some motion illusions. In Experiment 2 no vection was experienced in 31 out of 258 presentations and in Experiment 3 no vection at all was experienced for 367 out of 912 presentations. The explanation of vection and instruction for the task were also the same for each observer, if vection was solely caused by biases and demand characteristics, each observer would have been expected to experience vection for the motion illusions. However, one of the 45 observers in Experiment 2 and seven of the 71 observers in Experiment 3 experienced no vection.

Future research could further consider the role of individual differences in the perception of motion illusions [102] and design expanding and rotating motion illusion matched for illusion strength for each individual. Contrast sensitivity for example has been shown to affect the perception of the motion illusions, with individuals with higher contrast sensitivity perceiving stronger illusory motion [102]. Future research could additionally assess observers contrast discrimination thresholds to determine how they affect the perception of both expanding and rotating illusions. The expanding motion illusions in Experiment 2 and 3 could elicit an illusion of both expanding and contracting motion thereby potentially leading to illusions of both self-forward and -backward motion. Future studies could try and identify illusions that only elicit illusory self-forward motion in the observer which according to Bubka [31] and colleagues elicits the strongest sensation of vection which could further the understanding of differences in the effect of lateral motion and motion in depth on the strength and direction of vection.

The current experiments did not include a control condition. It is possible to manipulate the pattern in a way so that the illusory motion is much reduced, for example see [63]. By using such a control condition it would be possible to gauge whether experienced cybersickness, vection and head movements are caused by the perceived motion in the illusion rather than the gameplay at the beginning or the virtual environment in general. However, due to the relationship found between illusion strength and cybersickness as well as vection magnitude we believe that the motion perceived from the illusions is at least partially responsible for the experience of vection and cybersickness. Further research into the effects of Fraser Wilcox illusions on cybersickness, vection and head movements, however, should include a control condition to give more insight into the effects of perceived motion.

5.4 Effect of Perceived Visual Motion on Head Movements

Contradictory to expectations, head movements were not affected by the type of the illusion presented or by the strength of the perceived illusory motion (Experiment 1, 2, 3). Based on previous literature, head movements were expected to be elicited on the same plane as presented visual motion [64,103]. Stronger illusions were also expected to cause greater head movements [63]. Head movements in all three experiments were bigger in the anterior-posterior direction compared to the medio-lateral direction independent of the stimulus presented to the observer. It is possible that motion illusions result in weak motion signals that were not strong enough to cause sway in the observer. Observers eliciting more head movements in the anterior-posterior direction is in line with previous research, which found that during quiet upright stance more sway in the anterior-posterior direction is performed than in the medio-lateral direction [104,105]. Voluntary medio-lateral sway has been shown to be more difficult and energy demanding to perform compared to sway in the anterior-posterior direction, which could explain the dominance of anterior-posterior head movements in the three experiments [106]. Based on rotating motion illusions being perceived as moving more and eliciting a stronger sensation of vection, however, more head movements in the medio-lateral direction would have been expected. Roll vection could potentially affect head-orientation rather than head displacement which could explain these results.

In the current experiments the magnitude of head movements was analysed for the medio-lateral and anterior-posterior directions only. Future research should additionally focus on the relationship between roll, yaw and pitch head movements and cybersickness as well as vection. A new theory of cybersickness focusing on the differences in virtual and physical head pose (DVP) has focused on the effects of these rotational head movements [113] highlighting the relationship between these head movements and cybersickness. Additionally, future research could focus on temporal dynamics of head movements and their relationship to adverse symptoms experienced in VR.

5.5 Perceived Motion as Cause of Vection

Results from Experiments 2 and 3 confirm the notion that perceived motion can elicit vection and that no actual simulate motion is necessary to elicit the illusion of self-motion in an observer [20,32,107–109]. This is in line with previous research that has shown that motion aftereffects [107] as well as illusory motion [109] can elicit vection in the absence of an explicit motion stimulus. Previous studies investigating the effect of optimised Fraser Wilcox motion illusions found differing results depending on the motion direction of the illusion. Seno [33,109] and colleagues used simple expanding motion illusions and found that their stimuli were able to elicit vection in their observers whereas a rotating motion illusions used in Rosenblatt and Crane’s study did not elicit the illusion of self-motion in the viewer [110]. The current study confirmed findings by Seno and colleagues with expanding motion illusions eliciting vection but also found that rotating illusions were able to elicit vection contradicting Rosenblatt and Crane's findings. The rotating stimuli presented in the current study differed from the ones presented by Rosenblatt and Crane [110], the motion illusions used in their experiment consisted of repeated asymmetric patterns mapped onto a torus, giving the illusion of the inside of the torus either rotating clockwise or counter clockwise whereas the illusions used in the current experiment consisted of circles that appeared to rotate clockwise or counter clockwise. It is possible that the illusion of a torus rotating around an observer is less suitable in inducing self-motion compared to the simple rotating motion presented in the current study. Observers were able to select their optimal viewing distance for the motion illusions presented in Experiment 2 resulting in the stimuli covering between 5.72° and 41.11° of the FOV. Vection strength generally increases with increasing stimulus size [57–59], therefore, changing the viewing distance and thereby the size of the motion illusions could have affected the experience of vection. In Experiment 3, however, viewing distance was held constant for all stimuli and all observers (23°) resulting in similar findings of illusion strength on vection and cybersickness as well as illusion type on illusion strength suggesting that the size of the perceived motion stimulus did not significantly affect the experience of vection.

5.6 Relationship between Cybersickness, Vection and Head Movements

Vection magnitude seems to be strongly related to discomfort ratings, with illusions that elicited a stronger feeling of self-motion in the observer also leading to more cybersickness. This supports previous work showing a positive relationship between vection and cybersickness [24–26]. Vection magnitude was also related to head movements in the anterior-posterior direction in Experiment 3, with illusions that caused a stronger perception of self-motion in the observer also leading to more back and forth sway, however this was not the case in Experiment 1 and 2, suggesting that the relationship between vection and head movements induced by illusory motion is rather weak. Vection onset and duration times had no effect on cybersickness or head movements, suggesting that the three vection measures are possibly representing different processes involved during the experience of vection [111]. The relationship between cybersickness and head movements seems to be mainly driven by dizziness and possibly eye strain symptoms. Additionally, observers experiencing more vection were also more likely to experience dizziness and head movements. This suggest that the relationship between cybersickness and vection strongly depends on what adverse symptoms are measured which could explain previous contradictory findings regarding the nature of their relationship. Dizziness being the main symptom of cybersickness relating to both vection and sway also further highlights the role of postural stability for cybersickness research and would again suggest that sensory conflict rather than the accommodation vergence conflict contributed to adverse symptoms and vection, as the accommodation vergence conflict mainly results in adverse symptoms stemming from the visual system, such as headache or blurred vision [112].

The presented experiments tried to further explore relevant questions regarding the comfortable use of VR headsets as the experimental design was rather exploratory and used linear mixed effect models as form of analysis determining the sample size a prior to conducting the experiments would have been rather complicated [113]. Power observed in mixed effect analyses depends on the number of observations (trials) rather than on the sample size these designs are often also more powerful compared to analyses that generalise across participants or stimuli [114]. As the main findings of this work were replicated throughout the three reported experiments as well as in pilot studies and additional experiments reported in the supplementary information using various headsets (Oculus Rift CV1, HTC Vive Pro, Valve Index) and sample sizes (30 – 71 observers) authors believe that the findings are rather robust. Eleven of the observers participated in 2 of the three experiments (three observers participated in Experiment 1 and 2, three in Experiment 2 and 3 and five in Experiment 1 and 3), with none of the observers taking part in all three experiments and the rest of the observers only participating in one experiment, again indicating robust findings.

5.7 Conclusion

In conclusion, the current experiments found illusory motion is sufficient to elicit the experience of vection in VR environments. This has important consequences for VR environment design. The motion perceived in the static images was directly related to the observers experience of cybersickness and vection magnitude, the more motion was perceived the more vection and discomfort the illusion caused. The three experiments showed a rather complicated relationship between cybersickness, vection and head movements, and that dizziness seems to be the main link between the three phenomena. This suggests that the interplay of the visual and vestibular systems is important in the experience of cybersickness and vection, when stimuli are controlled for accommodation-vergence conflict. Finally, rotating contrast-based motion illusions are perceived as moving more compared to their expanding counterparts, an effect which was robust to attempts to minimise differences between the stimuli. It is possible this is due to a lack of expected stereoscopic information weakening the illusory motion in the case of the expanding illusions.

Declarations

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Conflicts of interest

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

Availability of data and material

Associated data for Experiment 1 can be downloaded from https://doi.org/10.6084/m9.figshare.13903106.v1, for Experiment 2 from https://doi.org/10.6084/m9.figshare.13903229.v1 and for Experiment 3 from https://doi.org/10.6084/m9.figshare.13903700.v1.

Authors' contribution

K.P. and L.O.H conceived the study; K.P., L.O.H., J.F. and P.D. designed the experiment; K.P. performed the experiment; K.P. analysed the data; K.P., L.O.H., J.F., P.D., and A.P. wrote the paper.

Ethics approval

All three experiments received ethical approval by the University of Lincoln's Ethics Committee.

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Figure Captions

Figure 1: Examples of the used motion illusion stimuli. A) and b) give examples of two rotating motion illusions whereas c) and d) show two examples of expanding motion illusions. A) and c) are examples of low spatial frequency stimuli and b) and d) are examples of high spatial frequency stimuli.

Figure 2: Experiment 1: Predicted illusion strength ratings for expanding and rotating motion illusions. 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 3: Experiment 1: Predicted head movements in medio-lateral and anterior-posterior direction. 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 4: Experiment 1: Predicted illusion strength ratings by discomfort ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

Figure 5: Experiment 1: Predicted head movements in the anterior-posterior direction by dizziness ratings. 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 6: Experiment 2: Predicted illusion strength ratings by discomfort ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

Figure 7: Experiment 2: Predicted vection magnitude ratings based on illusion strength. 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 8: Experiment 2: Predicted discomfort ratings based on vection magnitude ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

Figure 9: Example of a rotating motion illusion (a) and the corresponding stimulus (b). used in Experiment 3. Stimuli were based on the optimised illusions but matched for colour (all grey-scale) and spatial frequency content. Stimuli were also matched for perceived illusion strength, based on the 2AFC pilot study.

Figure 10: Experiment 3: Predicted vection magnitude ratings for expanding and rotating motion illusions. 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 11: Experiment 3: Predicted illusion strength ratings by discomfort ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

Figure 12: Experiment 3: Predicted a) vection magnitude ratings, b) vection onset times (s) and c) vection duration times (s) based on illusion strength. 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 13: Experiment 3: Predicted discomfort ratings based on vection magnitude ratings. Visualisation of the Regression model with residual plots based on the lmer analysis, obtained using the visreg package. All five discomfort models were overlayed into one plot.

Figure 14: Experiment 3: Predicted head movements in the anterior-posterior direction by vection magnitude. 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

Tables

Discomfort	Illusion type		Illusion Strength	
	Mean (Std) for rotating vs. expanding stimuli	Test-statistic	Increase in discomfort measure per increase in illusion strength (Std Error)	Test- statistic
Experiment 1				
General Discomfort	0.84 (1.34) vs. 0.68 (1.89)	F(1,782)= 4.32, p = .038*, f^2 = .005, ΔBIC = -2.3	0.09 (± 0.02)	F(1, 809.92) = 20.96, p <.001*, f^2 = .04, ΔBIC = 14
Headache	0.42 (1.01) vs. 0.39 (0.96)	F(1,782)= 0.37, p = .545	0.01 (±0.01)	F(1, 809.04) = 0.61, p = .435
Blurred Vision	0.87 (1.66) vs. 0.68 (1.39)	F(1,782)= 5.90, p = .015*, f^2 = .007, ΔBIC = -0.8	0.03 (±0.02)	F(1, 809.98) = 2.33, p = .128
Dizziness	0.95 (1.64) vs. 0.84 (1.47)	F(1,782)= 2.12, p = .145	0.14 (± 0.02)	F(1, 809.13) = 45.58, p <.001*, f^2 = .07, ΔBIC = 37.7
Eye Strain	1.08 (1.77) vs. 0.95 (1.55)	F(1, 782)= 3.15, p= .076, f^2 = .004, ΔBIC = -3.4	0.05 (± 0.01	F(1, 804.93) = 5.39, p = .020*, f^2 = .02, ΔBIC = -1.3

* statistically significant at p < 0.05

Table 1: Experiment 1: Descriptive statistics and test statistics for the models investigating the effect of illusion type as well as illusion strength on discomfort ratings (general discomfort, headache, blurred vision, dizziness and eye strain).

Discomfort	Illusion type		Illusion Strength	
	Mean (Std) for rotating vs. expanding stimuli	Test-statistic	Increase in discomfort measure per increase in illusion strength (Std Error)	Test- statistic
Experiment 2				
General Discomfort	-	-	0.21 (± 0.03)	F(1, 492.46) = 54.09, p <.001*, f^2 = .05, ΔBIC = 45.4
Headache	-	-	0.04 (± 0.02)	F(1, 490.20) = 3.24, p =.073
Blurred Vision	-	-	0.09 (± 0.03)	F(1, 488.71) = 11.85, p < .001*, f^2 = .02, ΔBIC = 5.5
Dizziness	-	-	0.28 (± 0.03)	F(1, 488.76) = 87.78, p < .001*, f^2 = .07, ΔBIC = 75.1
Eye Strain	-	-	0.14 (± 0.03)	F(1, 499.94) = 16.73, p < .001*, f^2 = .01, ΔBIC = 10.3

* statistically significant at p < 0.05

Table 2: Experiment 2: Descriptive statistics and test statistics for the models investigating the effect of illusion strength on discomfort ratings (general discomfort, headache, blurred vision, dizziness and eye strain).

Discomfort	Vection Magnitude		Vection Onset	
	Increase in discomfort measure per increase in vection magnitude (Std Error)	Test-statistic	Increase in discomfort measure per increase in vection onset (Std Error)	Test- statistic
Experiment 2				
General Discomfort	0.32 (± 0.05)	$F(1,312.81) = 46.52$, $p <.001$*, $f^2 = .18$, $\Delta BIC = 37.8$	-0.002 (± 0.004)	$F(1,309.08) = 0.19$, $p =.661$
Headache	0.14 (± 0.03)	$F(1,310.82) = 16.65$, $p <.001$*, $f^2 = .07$, $\Delta BIC = 10.5$	-0.005 (± 0.003)	$F(1,307.17) = 2.63$, $p =.106$
Blurred Vision	0.15 (± 0.04)	$F(1,306.22) = 12.98$, $p <.001$*, $f^2 = .10$, $\Delta BIC = 6.86$	-0.01 (± 0.004)	$F(1,302.92) = 6.33$, $p =.012$*, $f^2 = .17$, $\Delta BIC = 662.86$
Dizziness	0.39 (± 0.05)	$F(1,310.56) = 63.66$, $p < .001$*, $f^2 = .17$, $\Delta BIC = 52.80$	0.001 (± 0.005)	$F(1,306.88) = 0.07$, $p =.768$.
Eye Strain	0.17 (± 0.05)	$F(1,316.18) = 10.49$, $p < .001$*, $f^2 = .05$, $\Delta BIC = 4.60$	0.001 (± 0.005)	$F(1,312.47) = 0.01$, $p =.922$

* statistically significant at $p < 0.05$

Table 3: Experiment 2: Descriptive statistics and test statistics for the models investigating the effect of vection magnitude as well as vection onset on discomfort ratings (general discomfort, headache, blurred vision, dizziness and eye strain).

Discomfort	Illusion type		Illusion Strength	
	Mean (Std) for rotating vs. expanding stimuli	Test-statistic	Increase in discomfort measure per increase in illusion strength (Std Error)	Test- statistic
Experiment 3				
General Discomfort	1.05 (1.91) vs. 0.95 (1.89)	$F(1,1632)=2.72$, $p= .099$	0.10 (± 0.02)	$F(1, 1678.9) = 35.26$, $p <.001$*, $f^2 =.01$, $\Delta BIC = 27.57$
Headache	0.67 (1.47) vs. 0.69 (1.46)	$F(1,1632)=0.16$, $p= .691$	0.04 (± 0.01)	$F(1, 1691.2) = 6.32$, $p = .012$*, $f^2= .0004$, $\Delta BIC = -1.1$
Blurred Vision	1.33 (2.09) vs. 1.27 (2.02)	$F(1,1632)=1.00$, $p= .317$	0.08 (± 0.02)	$F(1, 1663.3) = 29.24$, $p <.001$*, $f^2 = .02$, $\Delta BIC = 21.6$
Dizziness	0.92 (1.73) vs. 0.83 (1.64)	$F(1,1632)= 1.91$, $p= .167$	0.17 (± 0.02)	$F(1, 1686.2) = 126.72$, $p <.001$*, $f^2 = .08$, $\Delta BIC = 114.9$
Eye Strain	1.19 (1.94) vs. 1.06 (1.84)	$F(1,1632)=6.11$, $p= .014$*, $f^2 = -0.01$, $\Delta BIC = -1.4$.	0.08 (± 0.01)	$F(1, 1661.3) = 35.01$, $p <.001$*, $f^2 = .02$, $\Delta BIC = 27.2$

* statistically significant at $p < 0.05$

Table 4: Experiment 3: Descriptive statistics and test statistics for the models investigating the effect of illusion type as well as illusion strength on discomfort ratings (general discomfort, headache, blurred vision, dizziness and eye strain).

Discomfort	Vection Magnitude		Vection Onset		Vection Duration	
	Increase in discomfort measure per increase in vection magnitude (Std Error)	Test-statistic	Increase in discomfort measure per increase in vection onset (Std Error)	Test- statistic	Increase in discomfort measure per increase in vection onset (Std Error)	Test- statistic
Experiment 3						
General Discomfort	0.19 (± 0.03)	F (1,997.47) = 38.84, p <.001*, f^2 = 0.02, ΔBIC = 31.4	0.001 (± 0.003)	F (1,995.84) = 0.03, p =.852	0.007 (± 0.005)	F (1,805.64) = 1.68, p =.196
Headache	0.02 (± 0.03)	F (1,976.37) = 0.65, p =.420	-0.002 (± 0.002)	F (1,996.08) = 0.96, p =.328	-0.004 (± 0.004)	F (1,593.09) = 0.63, p =.428)
Blurred Vision	0.07 (± 0.03)	F (1,996.64) = 6.55, p = .011*, f^2 = 0.01, ΔBIC = -0.3	0.0003 (± 0.002)	F (1,989.72) = 0.02, p =.894	0.003 (± 0.005)	F (1,897.40) = 0.31, p =.581
Dizziness	0.21 (± 0.03)	F (1,985.11) = 49.38, p < .001*, f^2 = 0.04, ΔBIC = 41.3	0.005 (± 0.003)	F (1,997.61) = 3.41, p = .065	0.001 (± 0.005)	F (1,650.90) = 0.05, p =.831
Eye Strain	0.06 (± 0.03)	F (1,992.96) = 4.62, p = .032*, f^2 = 0.04, ΔBIC = 41.2	0.001 (± 0.002)	F (1,984.68) = 0.18, p =.668	0.006 (± 0.005)	F (1,943.46) = 1.52, p =.218

* statistically significant at p < 0.05

Table 5: Experiment 3: Descriptive statistics and test statistics for the models investigating the effect of vection magnitude, vection onset as well as vection duration on discomfort ratings (general discomfort, headache, blurred vision, dizziness and eye strain