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published in

Displays

2019

DOI (link to publisher)

[10.1016/j.displa.2018.10.001](https://doi.org/10.1016/j.displa.2018.10.001)

document version

Publisher's PDF, also known as Version of record

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citation for published version (APA)

Kuiper, O. X., Bos, J. E., & Diels, C. (2019). Vection does not necessitate visually induced motion sickness. *Displays*, 58, 82-87. <https://doi.org/10.1016/j.displa.2018.10.001>

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Vection does not necessitate visually induced motion sickness[☆]

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ARTICLE INFO

Keywords:

Visually induced motion sickness

Vection, Optic flow

HMD

Virtual reality

ABSTRACT

Vection, i.e. a visually induced illusory sense of self-motion, is assumed to play an essential role in visually induced motion sickness (VIMS). However, its precise role is unknown. Following the sensory conflict theory, a constant state of vection is not expected to lead to a visual-vestibular conflict whereas variability in vection, i.e. change in vection strength over time, would. In this study we investigated whether variability in vection rather than vection caused VIMS in participants exposed to constant optic flow using a head-mounted display. Strongest possible vection (i.e. 100% on a 0–100% scale) was reported by 16 out of 18 participants at some point during the experiment, with a total average vection score over the experiment of 58.6%. Initial motion sickness symptoms were reported by 15 out of 18 participants, although only averaging 1.78 on an 11-point scale. Neither average vection strength nor variability in vection were significantly correlated with motion sickness. Relating our findings to the literature, we argue that vection should be understood not as a direct cause of VIMS, but as a perceptual state still depending on other visual factors before VIMS occurs. Vection by itself, even if it is experienced strongly, does not necessitate VIMS.

1. Introduction

Visually induced motion sickness (VIMS) is a type of motion sickness caused exclusively by visual motion rather than by physical motion. Its symptoms are, besides added oculomotor disturbances, principally the same as that of general motion sickness: pallor, cold sweat, dizziness, fatigue, nausea, potentially culminating in vomiting [1,2]. While the relation between physical motion and motion sickness is relatively well understood [3–5], the root cause or causes of VIMS in particular are not fully understood [6–9]. The principal framework in which motion sickness is most commonly explained is the sensory conflict theory [4,10–13]. This theory stipulates that a mismatch between sensed and expected motions is the origin of motion sickness, often resulting from discrepancy between visual, vestibular, and/or the proprioceptive sensory information. The relationship between physical motion and how it results in motion sickness has been studied extensively and produced predictive models (e.g. [14]). Exactly how moving visual scenes lead to motion sickness is less well-understood.

When an observer is stationary and visual motion is presented, this does not always lead to VIMS. Generally, VIMS is assumed to only arise when the observer experienced *vection*, an illusory sense of self-motion

brought on by visual cues [15]. However, while vection seems to be *necessary* for VIMS to occur, it has not been found to be *sufficient*. That vection plays an important, but ultimately non-decisive role in VIMS is reflected in the literature on this subject. For instance, many studies find a strong relation between vection and VIMS [16–19]. On the other hand, however, several studies find vection occurring without leading to VIMS [20–22]. While vection is generally the focus of VIMS research, various authors have questioned what to make of the ambiguous relationship vection has with VIMS [9].

An explanation for why vection is not consistently found to lead to VIMS already exists in the sensory conflict theory. Namely, vection by itself does not necessarily lead to a conflict between expected and sensed motion. A steady state of vection, i.e. constant vection strength over period of time, suggests a constant speed of self-motion, which does not lead to an expectation of vestibular response since the vestibular organs are only sensitive to *accelerations* and not to constant velocity. Rather than vection per se, only *variability in vection*, i.e. change in vection strength over time, suggests changes in velocity of self-motion and would produce a visual-vestibular conflict in a stationary observer. This point, that changes in vection might be the decisive factor in VIMS, has been explicitly raised by only a few authors [23,24].

[☆] This article is part of the Special Issue on VIMS 2017.

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<https://doi.org/10.1016/j.displa.2018.10.001>

Received 23 February 2018; Received in revised form 12 July 2018; Accepted 1 October 2018

Available online 04 October 2018

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In fact, Bonato et al. [24] found evidence for the hypothesis that variations in vection rather than only vection underlie VIMS. In their study, the authors presented participants with an alternating optic flow pattern in one condition, and a constant optic flow pattern in the other, and found that the alternating optic flow condition lead to lower average vection but increased variability in vection, and significantly higher reported VIMS. These findings further substantiate the premise that vection does not have a simple relation to VIMS. However, the use of two different conditions of optic flow does not rule out that the effect on VIMS was not directly a result of variability in vection. Rather, the condition of alternating optic flow could have simply constituted a more provocative stimulus independent of its effect on vection, for instance by increasing the visual-vestibular conflict.

Therefore, in this experimental study, we also aimed to answer the question whether it is vection, or rather *variability in vection* that leads to VIMS. Importantly, we opted to use a single constant optic flow stimulus to investigate exclusively the effect of variability in vection on VIMS, without altering optic flow. Due to the fact that under constant optic flow vection is experienced variably [25], a constant optic flow pattern was expected to equally lead to a usable measure of variability in vection in participants, without introducing confounding factors relating to changing the optic flow. Based on the sensory conflict theory, under which variable vection is theorized to lead to the increased visual-vestibular conflict, we expected to find a stronger (and significant) correlation between alterations in vection and VIMS as compared to average vection strength and VIMS.

2. Methods

2.1. Participants

Eighteen volunteers participated in the experiment (10 males, 8 females, mean age 25.2 ± 3.6). All had normal or corrected to normal vision and indicated to be free of vestibular problems.

2.2. Stimuli and apparatus

The stimulus pattern consisted of an array of white spheres against a dark background displayed using a HTC Vive head mounted display (HMD). The resolution per eye was 1080 by 1200 pixels with a refresh rate of 90 Hz. The full horizontal and vertical field of view were 110 degrees, approximately 90 degrees horizontal for each eye. The white spheres were modelled in the game engine Unity (version 5.6.1f1), and appeared in a semi-random pattern at the maximum viewing distance, going in a straight line towards the anterior-posterior plane of the participant (see Fig. 1). All spheres moved in unison in terms of speed and position relative to each other in the virtual

Fig. 1. The stimulus pattern used in the experiment. Within the 3D environment the white spheres steadily moved in a straight lines towards the anterior-posterior plane of the participant, resulting in radially expanding optic flow suggesting forward motion.

Table 1
11-point Misery SScale (MISC) [27].

Symptoms	Misc
No problems	0
Some discomfort, but no specific symptoms	1
Dizziness, cold/warm, headache, stomach/throat awareness, sweating, blurred vision, yawning, burping, tiredness, salivation, ... but no nausea	Vague 2
	Little 3
	Rather 4
	Severe 5
Nausea	Slight 6
	Fairly 7
	Severe 8
	(Near) 9
	retching
Vomiting	10

environment for the full duration of the experiment. Each individual sphere was in view for approximately seven seconds. When looking forward, as was explicitly instructed to the participant to ensure a similar exposure to the stimulus, participants viewed a radially expanding optic flow pattern suggesting forward motion. The HMD corrected for head movements to ensure the stimulus always appeared moving along an earth-fixed (rather than an observer-fixed) trajectory.

2.3. Measurements

Before and after exposure to the VR stimulus, participants filled out the Simulator Sickness Questionnaire (SSQ, [26]) and indicated their motion sickness score on the 11-point Misery Scale (MISC), see Table 1 [27]. Both these methods give an indication of motion sickness and are commonly used in studies concerning motion sickness, while the SSQ also subdivides nausea, oculomotor related discomfort, and disorientation. In addition, before the experiment participants filled out the Motion Sickness Susceptibility Questionnaire (MSSQ [28]), in order to assess their susceptibility to motion sickness compared to the expected average susceptibility of a representative sample.

To measure vection during the experiment, we constructed a simple hand-held device with a single continuous slider. The position of the slider corresponded linearly to a signal in the range of 0–100 (percent) that was logged at 10 Hz via USB in the same computer program that ran the stimulus. Participants were asked to report vection throughout the full ten minutes of the experiment. Prior to the experiment, participants were explained the concept of vection. When explaining use of the device to indicate vection, the extremes of the slider were explained as “0%: I have no sensation of moving myself, but rather the objects are moving around me” and “100%: I have the sensation I am moving past the objects, which are standing still”. Therefore, a score of 0% indicated a complete absence of vection, while a score of 100% indicated the strongest possible vection. Participants were told they should, at each moment for the full duration of the experiment, indicate their experienced vection on a continuous scale, i.e. they could indicate any percentage spanning the two extremes. For instance, if the participant positioned the slider halfway (at 50%), this implied the participant experienced both self-motion and approximately equally strong motion of the environment. The average vection score was calculated simply by the average score over the ten minutes.

Vection variability score was calculated by using the sum of the absolute of differences between each sample of vection data over the 10 min, analogous to path length. For example, if vection score during the 10 min would only rise monotonically from no vection (0%) to the strongest possible vection (100%), and then monotonically decreases back to no vection (0%), this would entail a total vection variability score of 200% (assuming no other slider input was given during the 10-

minute period). This method to calculate vection variability has the advantage over common measures for variation (e.g. standard deviation) in that increased change in vection response actually substantiates a higher score. For example, in the case of standard deviation a single reported change in experienced vection halfway through the experiment from no vection (0%) to complete vection (100%) would lead to the absolute maximum possible standard deviation score, while only a single change in experienced vection occurred. Conversely, the vection variability score we utilized we believe provides a better measure for changes in vection over time, without adding much complexity.

2.4. Procedure

Approval by the Ethics Committee of the Faculty of Human Movement Sciences of the VU University was obtained in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Before the experiment, participants were informed about the experiment and signed the informed consent form. Subsequently, they filled in the MSSQ, SSQ and indicated their MISC score as a baseline. Participants were handed the vection indicator device and were instructed to demonstrate the use of the device by indicating what the response should be either for complete vection (100%), or no vection at all (0%); this was done to ensure participants had a feel for the device since they had no visual feedback during the experiment once they put on the HMD. Participants put on the HTC vive, and were allowed to adjust the head mounted display until they indicated it was comfortable and they had sharp vision on a simple wireframe representation of the room, before the display was set to black again. Once the participants indicated they were ready to start, white noise was played over the headphones and the stimulus was initiated. After ten minutes, the stimulus and white noise stopped and participants were helped with taking off the head mounted display. Directly after taking off the HMD, participants again filled out the SSQ and reported their MISC score.

3. Results

All subjects were able to complete the experiment. Maximum possible vection, i.e. 100%, was reported by all but two participants at some point during the 10 min exposure. On average, vection scores were $58.6\% \pm 29.6\%$. MSSQ scores were on average 13.53 ± 13.45 , which falls between the 50th and 60th percentile in term of motion sickness susceptibility [28].

Reported motion sickness after the experiment was on average 1.78 ± 1.06 on the MISC scale, with on average 18.7 ± 10.1 for the SSQ total scores. The SSQ subscales showed on average 9.68 ± 8.14 *Oculomotor*, 21.7 ± 18.6 for *Disorientation*, and 10.6 ± 12.6 for *Nausea*. These reported scores correspond to 15 of the 18 subjects indicating an increase in MISC after the experiment. On the SSQ, 17 of 18 participants reported increase in at least one symptom. The two scales for motion sickness showed a strong correlation, $r = 0.753$, $p < .05$. The various sub-items of the SSQ did not significantly differ from the main SSQ score ($p > .05$), thus we opted to use exclusively the MISC scores as main indication of motion sickness occurrence in this study.

Variability in vection, as calculated by the total sum of the absolute changes over the 10 min, was on average $912.1\% \pm 595.1\%$. Some participants showed comparatively constant levels of vection, while others displayed clear alterations over time. This can also be seen in Fig. 2 which shows the reported vection over the 10 min for four different participants for illustration purposes.

A Pearson product-moment correlation coefficient was computed to assess the relationship between vection and motion sickness. We found no correlation between vection and sickness scores, $r = -0.28$, $p = .238$. We also did not find a correlation between variability in vection and sickness scores, $r = 0.19$, $p = .451$. See Fig. 3 for a scatterplot of motion sickness against both vection and vection variability.

4. Discussion

The stimulus we used was effective in inducing vection. Strongest possible vection (i.e. 100% on a 0–100% scale) was reported by 16 out of 18 participants at some point during the experiment, with a total average over the experiment of 58.6%. MSSQ scores indicated participants were of averagely susceptible to motion sickness [28]. The majority of participants indicated initial symptoms of motion sickness, albeit mostly mild symptoms (i.e. average MISC of 1.78 after the 10 min exposure); none of the participants experienced nausea at any point. Contrary to our expectations, we did not find vection scores and VIMS to be related, nor did we find variability in vection and VIMS to be related.

While the present study was not the first that did not find a relationship between vection and VIMS [20–22], we did expect to find evidence that variability in vection underlies VIMS, as was found by Bonato and colleagues [24]. Similar to our findings, a study by Nooij and colleagues [23] investigated variability in vection as a probable cause for VIMS and also found no indication that variability in vection underlies VIMS. In their study however, the authors did find a significant positive relationship between vection and VIMS, but acknowledge no clear-cut answers to exactly how vection and VIMS are related exist at this point. A possible explanation why Bonato and colleagues [24] found an increase in VIMS with increased variability in vection is that the alternating optic flow condition used by these authors not only lead to increased variability in vection, but also influenced additional factors, e.g. a (frequency dependent [29]) visual-vestibular conflict, leading to VIMS.

An aspect not often mentioned that might complicate determining the relationship between vection and VIMS is participants' inter-personal differences in terms of visual dependency. Individuals that score higher on the rod-and-frame test are shown to be more susceptible to simulator sickness [30]. Furthermore, higher field dependence, as measured by the rod-and-frame test, has been shown to modulate vection scores depending on the method of presentation of the vection stimulus [31]. These findings suggest that individuals experiencing vection might not necessarily weigh visual information equally, and therefore not have a similar perceptual visual-vestibular conflict potentially causing motion sickness, even despite similar motion sensation. Further complicating vection research is the fact that vection is not a concept participants are familiar with, and researchers have not always utilized a consistent definition [9]. In the present study, therefore, we aimed to provide all participants with a thorough and consistent explanation of vection to ensure they understood the concept.

An additional conceptual framework, building on the sensory conflict theory, to understand vection and (visually induced) motion sickness has been proposed in the form of resting frame information [32]. In this theory the 'rest frame' is the reference frame utilized by the central nervous system for spatial judgements, i.e. the frame perceived as stationary. Vection could lead to conflicting information on what is the correct rest frame, leading to VIMS. This theory can explain how strong vection, or even alterations in vection, does not necessarily lead to a larger conflict and subsequent VIMS, as long as the assumed veridical resting frame remains consistent. A second, associated, perspective on the potential principal component in VIMS is a different form of frame information, namely frame in terms of orientation. For orientation in space not only visual motion, but also frame information – i.e. horizontal and vertical lines – and polarity – i.e. objects suggesting the direction of the orientation of the true gravitational vector – are important [33]. However, the relative importance of various visual cues in determining orientation and self-motion is not fully understood. While visual stimuli such as the one used in the present experiment might be potent in influencing perception of motion, frame orientation information is absent. Vection could potentially be a separate phenomenon from the loss of orientation, caused by specific aspects of a visually ambiguous scene. An incongruence in the subjective vertical, i.e.

Fig. 2. Vection response (as given by the hand-held device) over the 10 min experiment of four typical participants. Some show large alterations in vection over time (e.g. 2nd from the top), while others are more constant in their perceived vection (e.g. 3rd from the top).

loss of orientation in respect to one's orientation to gravity, has been theorized to be the principal component in motion sickness [13,34]. If loss of orientation to vertical is the main factor in VIMS, rather than vection, this might explain why vection is sometimes found in the absence of VIMS. This hypothesis could be tested by comparing vection stimuli, and finding one stimulus that does not lead to VIMS but incites clear vection, and another stimulus that does lead to VIMS under equal levels of vection in the same participants.

The existence of vection without VIMS we found can be further potentially explained by the abstract stimulus we used. While background motion can facilitate VIMS [35], our stimulus did not suggest a coherent background, but rather only incrementally more distant independent objects. In addition, the virtual objects we utilized, abstract geometric spheres, made estimation of what their actual velocity was impossible. There is evidence that humans are already poor in general

at estimating velocity from exclusively visual cues [36], and that rather use mainly physical cues to estimate velocity [37]. Furthermore, it has been suggested that abstract stimuli might reduce the believability of motion stimuli, subsequently influencing how provocative these stimuli are in terms of inciting motion sickness [19]. These combined factors, i.e. ambiguities of the stimulus used, might explain how, while self-motion was experienced, in our experiment the actual neurological conflict underlying motion sickness might have been reduced, subsequently leading to low VIMS scores. Possibly a process of quarantining of abstract stimuli plays a role [38].

Considering the relatively high scores for vection we found, motion sickness scores we found were low when compared to similar studies [19] despite our 10-minute exposure being relatively long [24,39]. However, these studies utilized either visual yaw rotation or alternating optic flow stimuli, which might explain higher VIMS scores. In fact,

Fig. 3. Left: Average vection scores over the 10-minute experiment plotted against MISC scores. Right: Variability in vection, as calculated by the sum of the absolute differences over the 10-minute experiment, plotted against MISC scores.

Bonato and colleagues [24] found increased vection scores but reduced VIMS scores during constant optic flow compared to alternating optic flow. These findings also point in the direction that the intensity of vection does not predict VIMS, but rather that there are other factors in the visual scene that are decisive in VIMS. That our stimulus was successful in inciting high vection scores, but was compared to stimuli used by other studies not necessarily provocative substantiates this point. Further research could shed light on identifying those elements of a visual scene that are pivotal in inducing visually induced motion sickness, and those elements that are key in inducing specifically vection. Several potential causes for VIMS are discussed in an overview by Keshavarz and colleagues [9].

Our findings, similar to several prior vection studies, reinforce the notion that while vection plays a role in VIMS the relationship between them is not straightforward. VIMS remains a multi-faceted phenomenon, and no unifying theory that consistently predicts its occurrence exists. Other factors, such as frame information, might be essential components in understanding VIMS. The possibility that vection is not the decisive nor principal factor underlying VIMS should be considered.

Conflict of interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work.

Acknowledgement

This research was supported by Ford Research and Advanced Engineering. There was no sponsor involvement in the design of the experiment; in collection, analysis, and interpretation of the data; in writing of the report; nor in the decision to submit for publication.

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Ouren Kuiper studied philosophy and psychology at Utrecht University and attained his masters in Applied Cognitive Psychology in 2015. Currently, he is doing a PhD at the Vrije Universiteit Amsterdam in collaboration with the Dutch research institute TNO, on the topic of visual and vestibular perception and its relation to motion sickness, and specifically carsickness in autonomous vehicles.

Prof. dr. Jelte E. Bos holds an M.Sc. degree in physics and a Ph.D. degree in medicine. He is elaborating on the effects of physical and visual motion on human health, safety, comfort, and performance, with a particular interest in understanding self-motion perception and motion sickness, using neurophysiological and control theoretical knowledge. He is appointed by TNO, the largest applied scientific research organisation in the Netherlands, and holds a chair at the Faculty of Behavioural and Movement Sciences, Vrije Universiteit, Amsterdam. He has published over 100 peer reviewed papers as well as over 100 project reports (see www.jeltebos.info).

Dr Cyriel Diels has a background in cognitive psychology and has been working in both academia and industry in the field of automotive and transport human factors. He received his PhD from Loughborough University where he conducted his doctoral studies into Visually Induced Motion Sickness exploring the impact motion axes, frequencies and the role ofvection herein. He subsequently joined the Transport Research Laboratory (TRL) working with simulators researching driver behaviour and simulation fidelity and validity. He subsequently joined Jaguar Land Rover where he developed and evaluated novel HMI concepts. He is currently Academic Director at the National Transport Design

Centre (NTDC) at Coventry University exploring future vehicle design including the issue of motion sickness in automated vehicles.