The Role of Binocular Disparity and Motion Parallax in Cybersickness

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Abstract

Cybersickness is an enduring problem for users of virtual environments. While it is generally assumed that cybersickness is caused by discrepancies in perceived self-motion between the visual and vestibular systems, little is known about the relative contribution of motion parallax and binocular disparity to the occurrence of cybersickness. We investigated the role of these two depth cues in cybersickness by simulating a roller-coaster ride using a head-mounted display. Participants could see the tracks via a frame placed at the front side of the roller-coaster cart. We manipulated the state of the frame, so it behaved like: 1) a window into the virtual scene, 2) a 2D screen, 3) and 4) a window for one of the two depth cues, and a 2D screen for the other. Participants completed the Simulator Sickness Questionnaire before and after the experiment, and verbally reported their level of discomfort at repeated intervals during the ride. Additionally, participants' electrodermal activity (EDA) was recorded. The results of the questionnaire and the verbal ratings revealed the largest increase in cybersickness when the frame behaved like a window, and least increase when the frame behaved like a 2D screen. Cybersickness scores were at an intermediate level for the conditions where the frame simulated only one depth cue. This suggests that neither motion parallax nor binocular disparity had a more prominent effect on the severity of cybersickness. The EDA responses increased at about the same rate in all conditions, suggesting that EDA is not necessarily coupled with subjectively experienced cybersickness.

Keywords

Cybersickness, motion parallax, binocular disparity, virtual reality, roller-coaster

1. Introduction

Virtual reality (VR) and its applications have progressed enormously in recent years. Consumer-oriented VR devices have become very powerful and relatively inexpensive; thus, VR applications are in high demand in many areas, such as in therapy and rehabilitation (Rose, 1996; Merians et al., 2002), education (Kavanagh et al., 2017), and entertainment. Despite the significant improvements of the display quality and the latency of updating the 3D world to match the head-tracked position of head-mounted displays (HMDs), an enduring problem is the high number of users that experience "visually induced motion sickness" or "cybersickness" (Kennedy et al., 1993; Keshavarz and Hecht, 2011). Cybersickness is a sensation similar to traditional motion sickness and is strongly driven by visual stimulation in the absence of any physical motion. Typical symptoms include nausea, sweating, headache, disorientation, and dizziness (LaViola Jr, 2000). Several theories have been proposed to explain the underlying cause of visually induced motion sickness. The most prominent and widely accepted theory is the "sensory conflict theory" (Reason and Brand, 1975; Reason, 1978). It states that visually induced motion sickness results from a mismatch between, or within, the visual, vestibular, and somatosensory senses (Reason and Brand, 1975). For example, in an HMD-based VR scenario where visual motion simulates a driving car through the virtual scene, vision indicates self-motion, but the expected corresponding vestibular and somatosensory inputs that would normally be experienced from changes in accelerations and orientation during physical motion, are lacking. A possible explanation for why this can result in feeling sick is that our body entertains the idea that ingestion of a neurotoxic substance caused timing issues in the nervous system and responds with an attempt to empty the stomach from that substance (Treisman, 1977). Such a mismatch in indicated self-motion between different senses and the resulting cybersickness is a challenging problem for many VR applications that use navigation techniques that solely rely on visually moving through the virtual world. Although there is little disagreement about the role of sensory mismatch as one of the underlying causes of cybersickness, many other VR-specific technological and device-related factors have been found to play a moderating role in cybersickness. They include the frame rate of the HMD, size of the field-of-view, and the realism of the graphics rendering (for a review, see Weech et al. (2019)). Given that VR immersion is predominantly achieved by simulating a visual world and by the contingency between the user's active movements and the resulting visual consequences (Slater, 2009), it might not be surprising that most factors that affect cybersickness concern the visual quality and experience provided by VR devices.

An immersive virtual environment elicits a sense of presence in users, that is, a subjective feeling of being at a particular location in that environment and being able to actively change that location contingent on one's body movements (Slater et al., 1995; Lombard and Ditton, 1997; Troje, 2019). The illusory nature of being in a virtual environment is highly mediated through simulating two prominent depth cues, binocular disparity (stereopsis) and motion parallax. While binocular disparities are simulated by presenting each eye with a slightly different image, simulating motion parallax is achieved by tracking the user's head position and orientation and by updating the rendered 3D simulated scene in real time accordingly. Our experiment is designed to test the role of binocular disparity and motion parallax in cybersickness by generating situations in which these two depth cues provide consistent or incongruent information.

1.1. Visual and technological factors contributing to cybersickness

Research efforts to improve user comfort in VR by understanding and resolving factors that contribute to cybersickness have identified a number of technological and device-related factors. For example, low visual display frame rate was found to lead to increased cybersickness since extremely low frame rate and the associated visual lag presumably leads to a cue conflict between the vestibular and visual senses (Jones et al., 2004; Chen and Thropp, 2007). Rendering quality of the environments can also affect the chances of cybersickness to occur (Davis et al., 2015; Weech et al., 2019; Nichols et al., 2000). For example, when presenting participants with a roller-coaster ride in an environment with realistic texture resulting in a dense optic flow field, chances of inducing cybersickness were found to be significantly higher than in a simpler and more abstract environment (Davis et al., 2015). Similarly, it has been suggested that increasing the extent of the observable virtual world (i.e., the field-of-view) and thus the amount of optic flow also results in higher cybersickness (Lin et al., 2002; Harvey and Howarth, 2007; Duh et al., 2001). For instance, Seay et al. (2002) tested the effect of the size of the field-of-view on cybersickness using a driving simulation task. Results revealed a significant main effect of the field-of-view angle, 180° vs. 60°, where participants in the condition with the larger field-of-view, showed significantly higher cybersickness levels. Keshavarz et al. (2011) compared sickness ratings of participants after exposing them to a nauseating stimulus presented either on a large projection screen, on the same projection screen with a mask that restricted them from seeing the lab environment, or in an HMD. Participants in the projection group without a mask reported significantly higher levels of cybersickness compared to the other two conditions. The authors concluded that the higher cybersickness scores could be a result of the intra-visual conflict between the optic flow on the projection screen, and the stationary surrounding in their peripheral vision. However, an alternative explanation could be the differences in the field-of-view size and thus the overall amount of optic flow, as has been found in other studies (Harvey and Howarth, 2007; Duh et al., 2001; Seay et al., 2002).

1.2. The role of binocular disparity and motion parallax in cybersickness

Several studies have investigated the effect of binocular disparity on cybersickness under conditions where motion parallax was not simulated. The majority of these studies have reported enhanced symptoms of cybersickness under stereoscopic viewing conditions. For instance, some measures of visual discomfort, such as eye strain (a symptom of cybersickness), were significantly increased in a condition with binocular disparity (introduced with either shutter or polarized 3D glasses) as compared to a conventional 2D screen (Lambooij et al., 2011; Emoto et al., 2004). Keshavarz and Hecht (2012) tested the effect of binocular disparity on cybersickness during a virtual roller-coaster ride presented by a stereoscopic projector. Cybersickness scores were significantly higher when viewing the scene through shutter glasses in the condition where the stimuli were shown in 3D mode than in the 2D condition. In another study, participants viewed a video recorded by a camera moving along streets projected on a stereoscopic TV screen. The reported sickness scores were significantly higher in the condition with shutter glasses that were used to introduce binocular disparity, as compared to the 2D screen condition (Naqvi et al., 2013).

There are also some studies that did not find differences in cybersickness scores between conditions with or without binocular disparity. For example, IJsselsteijn et al. (2001) tested the effect of binocular disparity on cybersickness by showing participants a video from inside a rally car traversing a curved track with high speed using a stereoscopic projection screen and polarized 3D glasses. They reported no significant difference between the binocular and synoptic conditions where the non-stereo condition was obtained by presenting the left-eye video stream to both eyes. However, in their experiment, participants viewed the stimuli for only 100 seconds which might have been too short to induce any symptoms of cybersickness. No effect of binocular disparity was also reported in another study where participants were instructed to give a 5-minute virtual talk in front of an audience of virtual characters when using stereoscopic or non-stereoscopic renderings presented in a Z800 VR helmet (Ling et al., 2013). Although it is unclear whether binocular disparity was corrupted by using synoptic or monocular stimulation, a possible reason for obtaining these results is that the task did not involve any passive motion that would create a visual-vestibular conflict.

The number of experiments investigating the role of motion parallax in cybersickness is limited. Boustila et al. (2017) investigated the effect of binocular disparity and motion parallax on presence and cybersickness in a virtual environment rendered on a large projection screen. They placed participants in virtual rooms and tested distance perception in four different conditions where they manipulate binocular disparity and motion parallax using shutter glasses with head tracking either enabled or disabled. The results revealed no significant effect of binocular disparity or motion parallax on cybersickness. To test the role of motion parallax in inducing cybersickness, Howarth and Finch (1999) conducted an experiment in VR where in one condition, participants' heads were fixed, while in the other condition, they were allowed to move their head freely. Introducing motion parallax by allowing participants to move their head significantly increased sickness ratings.

The research summarized above suggests that when exposing participants to optic flow in a virtual environment that mimics characteristics of the real world through the simulation of motion parallax and binocular disparity, they experience more sickness than when being presented with the same virtual scenario on a 2D screen. Interestingly, the amount and extent of visual flow as well as the vestibular stimulation are identical in both situations. The information that self-induced motion parallax and binocular disparity provide is different in principle, but neither communicates information about self-motion in itself. The crucial difference seems to be whether or not the visual and vestibular systems are expected to register corresponding information about self-motion. Troje (2019) suggests that the visual brain operates in different perceptual modes when processing visual space of the world in front of our eyes, on the one hand, and looking at pictures or screens, on the other hand. According to that idea, the received pattern of binocular disparity and motion parallax when observing either visual or pictorial space determines whether the visual system is in "presence mode" or "picture mode" respectively. In presence mode, the observers have a defined location in space that results from the sensorimotor contingencies between their own active motion and the resulting retinal flow. Changes in location perceived visually are expected to correspond to vestibular input that would be experienced from changes in acceleration and orientation during physical motion. In picture mode, the observers do not have a defined location in the scene that changes contingent on their own motor behaviour and thus visually perceived changes in location in the pictorial world are not expected to be reflected in corresponding vestibular input.

1.3. Study aim

The aim of the current study was to investigate the relative contribution of motion parallax and binocular disparity to cybersickness. To this end, we designed a virtual environment in which participants experienced a roller-coaster ride using an HMD. Due to the drastic and quick changes in speed and moving direction that are experienced during a roller-coaster ride, this scenario lends itself well for an experiment on cybersickness. Participants were situated in an enclosed roller-coaster cart and viewed the tracks through a special frame, the "Alberti Frame"[1], placed at the front side of the cart. In the different conditions, we manipulated the state of the Alberti Frame so it behaved like: 1) a window into the virtual scene, 2) a 2D screen on which the same scene was projected, 3) and 4) a window with respect to one of the two depth cues, and a 2D screen with respect to the other. Using the same virtual scenario for simulating motion parallax and binocular disparity in the different experimental conditions allowed us to control for potential confounding factors that were shown to play a role for cybersickness, such as differences in rendering quality and field-of-view. We measured cybersickness both subjectively

[1]The virtual "Alberti Frame" makes reference to Leon Battista Alberti, the Italian Renaissance architect, artist, and mathematician who, in the 15th century, worked out the geometry of central projection. One of his techniques involved systematically copying the optic array seen from a fixed viewpoint through an empty frame onto the canvas spanned by a second frame.

with a questionnaire, and objectively by recording physiological responses. Participants' electrodermal activity (EDA) was chosen as a measure of physiological responses as it was previously shown that symptoms of cybersickness are associated with increased EDA (Kim et al., 2005; Hu et al., 1991).

We expected higher susceptibility to motion sickness in those participants exposed to the window condition than in those exposed to the 2D screen condition. In the intermediate viewing conditions, the visual system faces a puzzling situation since the Alberti Frame behaves like a window in terms of one depth cue, and like a 2D screen in terms of the other. These two conditions are somewhat intermediate between the window and screen condition. Accordingly, we may expect that these two additional conditions lie somewhere between the 2D screen and the window condition – at least if the increase in susceptibility to cybersickness from the 2D screen to the window condition is additively carried by independent changes of binocular disparity and motion parallax. Note that active motion parallax is not just a visual quality but a sensorimotor quality as it evaluates the visual consequences of active body motion. Simulating motion parallax on the Alberti Frame provides sensorimotor contingencies that establish a sense of location with respect to the environment behind the frame. While simulating stereoscopic cues on the frame provides more depth information as compared to the 2D screen condition, it does not provide the observers with an actively controlled location in the scene. Thus, if we assume that the sensorimotor predictions inherent to motion parallax are more important to propel the visual processing from picture mode into presence mode, then we may predict to observe more cybersickness in the condition where the Alberti Frame simulates motion parallax than when only stereoscopic cues are simulated.

2. Methods

2.1. Participants

We chose a desired sample size of 15 participants per condition (60 participants in total). All participants had normal or corrected-to-normal vision. To reduce the number of dropouts of our experiment due to high susceptibility to motion sickness, we set a pre-selection criterion and only included participants that scored below 8 on a 10-point scale when answering the following question prior to the experiment: "In daily life, how susceptible are you to motion sickness? (e.g., while travelling in a car)" (1 = "Not susceptible at all", 10 = "Extremely susceptible"). All of the participants that signed up for the experiment passed this pre-selection criterion. Participants were randomly assigned to one of the four experimental conditions (see Table 1 for descriptive statistics of the participants). Eight participants withdrew from the experiment (six from the window condition, and two from the intermediate condition where only binocular disparity was simulated on the Alberti Frame). Their data was not included in the final analysis and these participants were replaced with new participants. Participants were compensated with course credit for their participation. The experiment was approved by the Office of Research Ethics of York University and was conducted in accordance with the Declaration of Helsinki.

Table 1 Demographic characteristics of the participants in the four different experimental conditions (BD = binocular disparity; MP = Motion Parallax). In [BD = 1, MP = 1], the frame behaves like a window, in [BD = 0, MP = 0] the window behaves like a picture

Condition	Participant Sex	M_{age} (SD)
[BD = 1, MP = 1]	4 Males, 11 Females	21 (4.55)
[BD = 1, MP = 0]	4 Males, 11 Females	18.93 (1.22)
[BD = 0, MP = 1]	4 Males, 11 Females	21.53 (4.79)
[BD = 0, MP = 0]	5 Males, 10 Females	19.6 (2.5)

2.2. Apparatus and Virtual Scene

The virtual environment was designed in the Unity game engine and presented by means of an HTC VIVE Pro HMD with a resolution of 2880 x 1600 px (1280 x 1440 px per eye with 1280 x 1280 px binocular field) and a refresh rate of 90 frames per second. The virtual scene was generated and controlled by a high-end graphics computer (Intel Core i7 CPU, 16 GB of RAM and a NVIDIA 1080 GTX graphics card).

The roller-coaster was designed using the Dreamteck Splines Unity package and was placed in a realistic simulation of a natural environment containing trees and mountains created with the GAIA Procedural Worlds Unity package (Fig. 1a). The cart had closed walls except for the Alberti Frame at the front side. The roller-coaster cart was 1.5 m high, 2.5 m long and 2 m wide. The Alberti Frame was 1.5×1.3 m large and was placed 1 m away from participants.

There were four different conditions:

1. $[BD = 1\ MP = 1]$: The Alberti Frame simulated a normal window, as reflected by both stereoscopic and parallactic cues.
2. $[BD = 0, MP = 0]$: Both motion parallax and binocular disparity simulated the existence of a flat 2D screen spanned within the opening of the frame. The scene projected on that screen was the monocular view taken from the cart-fixed position occupied by the participant's nose-bridge when first entering the experiment.
3. $[BD = 1, MP = 0]$: Binocular disparity was identical to condition (1), but parallax was like in condition (2). Thus, the Alberti Frame behaved like a window with respect to binocular disparity, but like a 2D screen with respect to parallax.
4. $[BD = 0, MP = 1]$: Binocular disparity was identical to condition (2), but parallax was like in condition (1). Thus, the Alberti Frame behaved like a 2D screen with respect to binocular disparity, but like a window with respect to parallax.

During the experiment, participants were placed inside the roller-coaster cart (Fig. 1b) and experienced the roller-coaster ride through the Alberti Frame. To create a realistic experience of a roller-coaster ride, the speed of the cart varied depending on the track's local inclination between 7 m/s and 20 m/s. One lap lasted 60 seconds and was repeated 10 times consecutively without breaks resulting in a total roller-coaster ride of 10 minutes.

2.3. Measurements

Cybersickness was assessed via the Simulator Sickness Questionnaire (SSQ) as a subjective measure (Kennedy et al., 1993) of sickness. The SSQ contains 16 symptoms related to cybersickness that have to be rated on a 4-point Likert scale where the numbers reflect the level of severity of the corresponding symptom (from 0 (none) to 3 (severe)). The questionnaire provides a total score (SSQ-T), as well as scores for three different sub-scales: nausea (SSQ-N), oculomotor (SSQ-O), and disorientation (SSQ-D).

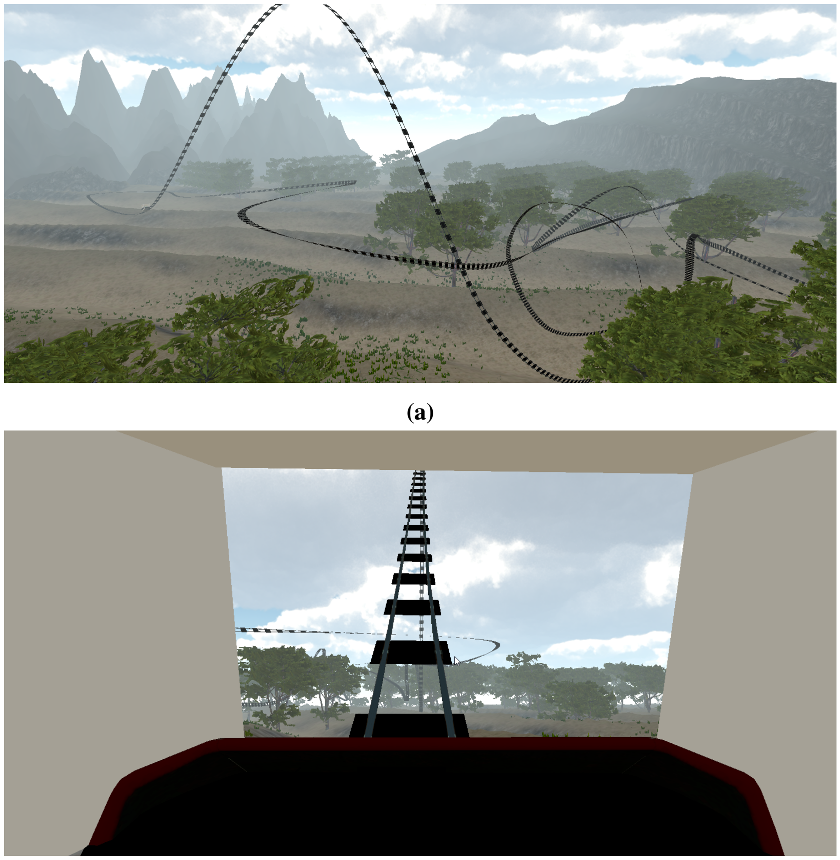
Moreover, we recorded EDA as a potential objective measure of cybersickness with the ProComp Infiniti physiological recording device with a sampling rate of 8 Hz. The EDA sensors were attached onto participants' index and ring finger. Participants' EDA was recorded for two minutes before the roller-coaster ride to get a baseline, and during the 10 minute duration of the roller-coaster ride. We followed the same procedure to analyze the EDA data as Dennison et al. (2016). From the raw data, each participant's EDA was averaged within 2-minute intervals to analyze the time course of participants' EDA during the roller-coaster ride.

In addition, participants' well-being and the potential gradual increase of their cybersickness was monitored by asking them to rate the following question at one-minute intervals during the experiment: "How do you rate your feeling in terms of general discomfort and nausea?". Participants answered the question on a 10-point Likert scale: from no nausea/discomfort (1) to very nauseated/uncomfortable (10). Both question and answer were provided verbally. Answers were recorded by the experimenter.

2.4. Procedure

Before starting the experiment, the experimental procedure was explained to each participant and they were given a consent form. Participants were explicitly informed that they could withdraw from the experiment whenever they felt uncomfortable or sick. They then filled out the SSQ (pre-SSQ) before being guided to the experimental room where they were equipped with the EDA sensors. During the experiment, participants were asked to stand upright and hold onto handles placed at hip-height in order to keep their balance during the roller-coaster ride. We reasoned that perceptual differences between the experimental conditions would be more pronounced when standing because natural body sway and visually induced changes in body posture would elicit more motion parallax.

The experiment started with a two minute baseline interval where the cart was stationary. The goal of this was to record participants' baseline for EDA before starting the roller-coaster ride and give participants time to get familiar with the virtual environment. After two minutes, the experimenter started the roller-coaster ride by pressing a button on the keyboard. Each minute, the experimenter asked participants about their general feeling of nausea and discomfort and wrote down the verbal



(a)

(b)

Fig. 1 (a) Screenshot of the virtual environment and the roller-coaster tracks; (b) Screenshot of the participant's view of the virtual environment from the inside of the roller-coaster cart. The horizontal extent of the opening subtended 74° from the default location of the observer's eyes

response. Upon completing the 10-minute roller-coaster ride, participants immediately filled out the SSQ again (post-SSQ). In case participants felt sick after the experiment, they were advised not to leave the laboratory until they had completely recovered from all symptoms.

2.5. Data Analysis

The verbal sickness ratings and participants' EDA were measured repeatedly over time, thus, the assumption of independence was not satisfied. Therefore, in order to take repeated measures into account, we used a linear mixed model to analyze verbal reports and EDA. All statistical analyses were done in R using the $lme4$ package (Bates et al., 2014). Analysis of variance (ANOVA) was used to asses the effect of the different conditions on SSQ scores.

3. Results

Verbal Cybersickness Ratings

The linear mixed model that was used to analyse the verbal ratings, included both random intercept and random slopes. The following model was fitted (in Wilkinson-notation; Wilkinson and Rogers (1973)):

$$\text{Verbal ratings} \sim 1 + \text{Time} + (1 + \text{Time}|\text{Condition}) \qquad \text{(Eq. 1)}$$

We did not include participant as a variable due to multicollinearity with condition. In order to ensure that our models were accurate, we compared the full model to simpler models, including a simple multiple regression and a mixed model with only random intercepts. The full model with random slopes and intercepts fits the data significantly better than the simpler models (Table 2).

The results showed that the intercepts of all conditions started at the same value (1, no nausea and discomfort) which means that participants' verbal reports at the baseline were not different from each other across the four experimental conditions. Verbal ratings increased significantly over time in all conditions, however the rate of increase (slope) was not the same across the conditions (Table 3). Verbal scores increased with the highest rate in the condition where the Alberti Frame was set to a window ([BD = 1, MP = 1]) as compared to the other three conditions. The verbal ratings in the two intermediate conditions ([BD = 1, MP = 0] and [BD = 0, MP = 1]) also increased with time, however, their slopes were similar to each other. Participants' verbal sickness ratings increased over time with the lowest slope in the condition where the Alberti Frame was set to a 2D screen ([BD = 0, MP = 0]).

Fig. 2 demonstrates the verbal sickness indications as predicted by the mixed model (Eq. 1) alongside with the mean raw verbal ratings at each time point for all conditions. Although verbal sickness ratings increased in all conditions, the slope in the condition where the Alberti Frame simulated a flat 2D screen ([BD = 0, MP = 0]) was very low. The change of verbal score in this condition is approximately one unit (from 1.07 to 1.97) over the course of ten minutes, which is a much smaller effect size compared to the effect size of other conditions, specifically in the condition where the Alberti Frame simulated a window ([BD = 1, MP = 1]), where we observed an approximate change of 4.1 units in ten minutes.

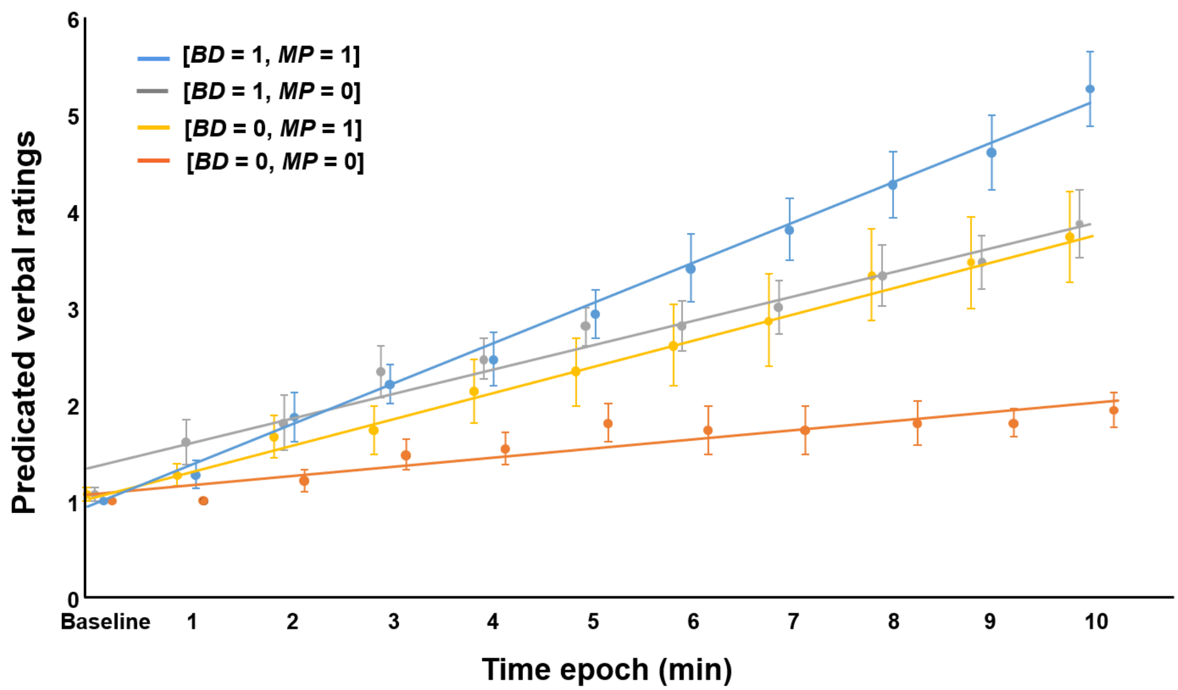


Fig. 2 Cybersickness ratings as predicted by the mixed model (Eq. 1) and mean raw verbal ratings at each time for all experimental conditions. Lines represent the model's fitted regression lines for each condition. BD = binocular disparity; MP = motion parallax. 0 = not simulated by the Alberti Frame; 1 = simulated by the Alberti Frame. Error bars represent SEM

Table 2 Model Comparison

Model	AIC	Log likelihood	Comparison to full model
Full model (random intercepts and random slope)	1167.7	-1029.78	N/A
Model with random intercepts only	2067.6	-1029.78	$p < .0001$
Simple multiple regression	2178.3	-1086.16	$p < .0001$

Table 3 Full mixed model parameters including fixed and random effects

Fixed Effects				
Parameter	Estimated Value	Standard Error	t-value	p-value
Intercept	0.827	0.12	6.37	0.007
Time	0.259	0.06	3.91	0.029
Random Effects				
Parameter	Estimated Value	Standard Error	t-value	p-value
[BD = 1, MP = 1] intercept	.95	.09	3.455	.001
[BD = 1, MP = 0] intercept	1.22	.09	5.232	<.0001
[BD = 0, MP = 1] intercept	1.01	.09	7.517	<.0001
[BD = 0, MP = 0] intercept	1.07	.09	6.801	<.0001
[BD = 1, MP = 1] slope	.41	.037	10.652	<.0001
[BD = 1, MP = 0] slope	.24	.037	6.422	<.0001
[BD = 0, MP = 1] slope	.27	.037	6.916	<.0001
[BD = 0, MP = 0] slope	.09	.037	2.401	.019

EDA

Participants' EDA responses were normalized with respect to the baseline epoch to account for individual differences in the baseline period before the roller-coaster ride started. We applied the same linear mixed model as for the verbal cybersickness ratings to analyze the EDA responses. However, comparing the full model to the simpler models illustrated that introducing random slopes or intercepts did not improve the model (Table 4). This indicates that the EDA scores did not significantly differ between the four conditions throughout the experiment. We therefore chose the simplest linear regression model to analyze the effect of time on EDA responses across the four conditions.

Table 4 Model Comparison

Model	AIC	Log likelihood	Comparison to full model
Full model (random intercepts and random slope)	1438.5	-714.83	N/A
Model with random intercepts only	1441.7	-715.24	p = .662
Simple linear regression	1442.6	-715.79	p = .588

A significant regression equation was found (F(1,358) = 44.45, $p < .0001$). While the estimated intercept was not significantly different from zero, participants' average gain in EDA was significantly greater than zero which indicates a main effect of time on EDA scores (Table 5).

Fig. 3 illustrates EDA responses over time for each group and the fitted regression line. EDA increased in all groups without a significant difference between conditions.

Table 5 Linear regression parameters for EDA

Parameter	Estimated value	Standard error	t-value	p-value
Intercept	.09	.16	0.66	.50
Slope	.36	.05	6.66	$< .0001$

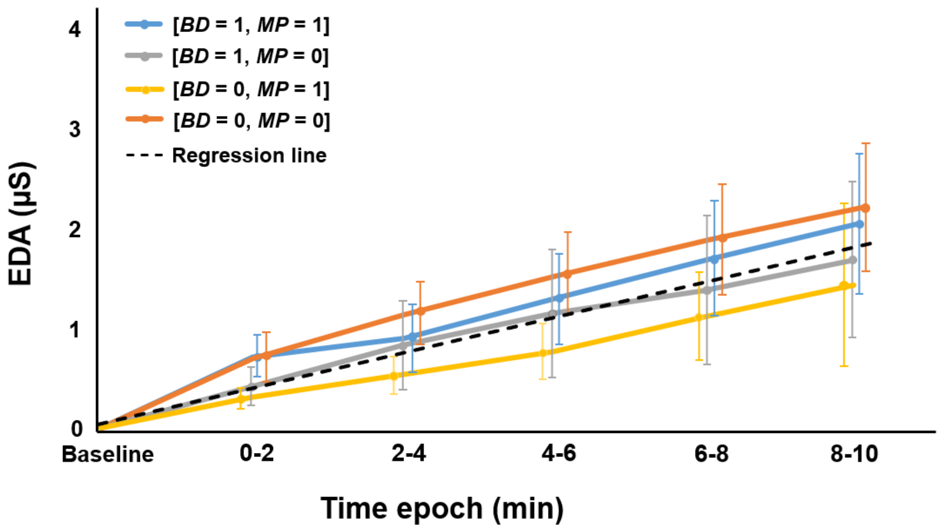


Fig. 3 The chronological sequence of the EDA results for all four experimental conditions and the fitted regression line. BD = binocular disparity; MP = motion parallax. 0 = not simulated by the Alberti Frame; 1 = simulated by the Alberti Frame. Error bars represent SEM

SSQ Scores

We subtracted the pre-SSQ scores from the post-SSQ scores for each participant and performed one-way ANOVAs to investigate potential differences in the SSQ pre-post difference scores between the experimental conditions ([BD = 1, MP = 1], [BD = 0, MP = 0], [BD = 1, MP = 0], [BD = 0, MP = 1]) for each of the SSQ sub-scales.

For the total score, the results showed a main effect of condition, F = (3, 56) = 7.35, p = .0003. Post-hoc analyses (Bonferroni corrected t-tests with an adjusted alpha level of 0.0125) showed a significantly higher SSQ-T score for the [BD = 1, MP = 1], [BD = 1, MP = 0], and [BD = 0, MP = 1] conditions compared to the [BD = 0, MP = 0] condition (p = 0.0001, p = 0.009, p = 0.01, respectively). The SSQ-T for the [BD = 1, MP = 1] condition was also higher than the [BD = 0, MP = 1] and [BD = 1, MP = 0] condition, however, it did not reach statistical significance (p = .403, p = .404, respectively). Moreover, the two intermediate conditions frame did not differ form each other (p = .99).

The analyses on the SSQ sub-scales also revealed a main effects of condition: SSQ-N, F(3,56) = 6.7, $p = 0.001$, SSQ-O, F(3,56) = 5.9, $p = .001$ and SSQ-D: F(3,56) = 6.85, $p = .001$. Post-hoc analyses showed the same pattern for all SSQ sub-scales as for the SSQ-T (Fig. 4) with significantly higher cybersickness scores when the Alberti Frame simulated at least one of the depth cues as compared to when the two cues were absent on the Alberti Frame. Once more, the scores in the [BD = 1, MP = 1] condition were higher than the intermediate ones but not significantly different from them. The scores of the intermediate conditions were very similar to each other for all of the sub-scales. Fig. 4 illustrates the SSQ scores for all sub-scales.

4. Discussion

In this study, we investigated the relative contribution of motion parallax and binocular disparity to cybersickness in an HMD-based virtual environment using a virtual roller-coaster ride. We measured subjectively perceived cybersickness using the SSQ questionnaire and verbal ratings collected repeatedly during the course of the ride. We also recorded participants' electrodermal activity (EDA). We expected that participants would experience more cybersickness symptoms when they viewed the roller-coaster ride through a window ([BD = 1, MP = 1]) compare to when they viewed it on a simulated 2D screen ([BD = 0, MP = 0]), and that this difference would be reflected in both subjective and objective measures.

The results of the verbal cybersickness ratings and SSQ scores showed that cybersickness symptoms were indeed stronger

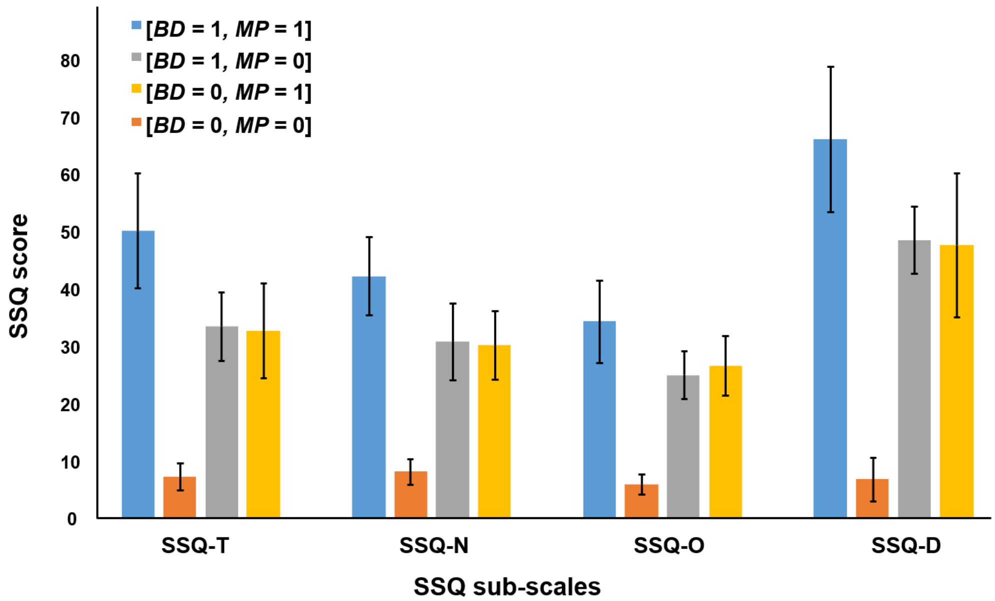


Fig. 4 Pre-post SSQ difference scores for all 4 conditions. SSQ-T: total score, SSQ-N: sub-scale nausea, SSQ-O: sub-scale oculomotor, SSQ-D: sub-scale disorientation. BD = binocular disparity; MP = motion parallax. 0 = not simulated by the Alberti Frame; 1 = simulated by the Alberti Frame. Error bars represent SEM

in the window condition than in the 2D screen condition. The SSQ scores after exposure to the roller-coaster ride, as well as the rate of increase in verbal scores during the ride, were significantly higher in the window condition as compared to the 2D screen condition. The fact that this pattern was also reflected on the individual SSQ sub-scales speaks to the robustness of this finding. These results are in line with previous studies that found significantly increased cybersickness when presenting the same virtual scene in an HMD as compared to on a desktop or large screen (Rebenitsch and Owen, 2016; Dennison et al., 2016). Whereas comparisons across different visual display types entail a number of possible confounding factors (e.g., differences in field-of-view, rendering quality, immersiveness), using the Alberti Frame to simulate a window and a 2D screen in the same virtual setting allowed us to manipulate parallax and binocular disparity independently and without any confound with other depth cues or extrinsic factors.

The difference in experienced cybersickness in the window and picture conditions may reside in the fundamental differences in how visual and pictorial spaces behave and how they are processed by our visual system. Visual space affords that we can move and interact with objects in it; we have a defined location in that space information about which is conveyed by sensorimotor contingencies between our own active movements and their visual consequences. In pictorial space, in contrast, while we can understand the spatial relationship between the depicted object in the scene, we do not have a true location in that space. We may adopt the camera's location, but that location does not behave like normal locations do: It does not change as we move our head in space (Koenderink and van Doorn, 2012, 2008).

A possible explanation for the different experiences when viewing visual and pictorial spaces is that our visual system operates in two different perceptual modes depending on whether it processes visual space or pictorial contents (Troje, 2019). In our experiment, when the Alberti Frame behaved like a window, participants experienced the visual space between themselves and the opening of the cart as extending behind the frame. In this situation where the visual system operates in presence mode, the visual flow is interpreted as self-motion which conflicts with the absence of the corresponding vestibular and somatosensory inputs that would be expected during physical movement, and thus cybersickness occurs. When the Alberti Frame behaved like a 2D screen, the visual system operates in picture mode in which the visual flow of the roller-coaster ride is not or only to a small extent interpreted as self-motion and is thus not in conflict with information provided by the vestibular system.

Previous research suggests that visually induced motion sickness is usually accompanied by the experience of compelling self-motion (vection), though it might not be a necessary prerequisite for motion sickness to occur (for a review, see Keshavarz et al. (2015)). Although we did not monitor the onset and extent of perceived vection in our experiment, subjective reports of our participants indeed suggested that they experienced more vection in the window condition than in the 2D screen condition. We can speculate that being in presence mode promotes the interpretation of the optic flow as self-motion.

For the intermediate conditions where the Alberti Frame behaved like a window with respect to one of the two depth cues, and like a 2D screen with respect to the other ([BD = 1, MP = 0 and BD = 0, MP = 1]), we predicted that cybersickness levels could range between the window and 2D screen condition. This result would be expected if the difference in cybersickness between the two conditions is additively carried by independent changes of binocular disparity and motion parallax. Furthermore, we hypothesized that participants would get more sick in the condition where only motion parallax was simulated ([BD = 0, MP = 1]) because it provides the participant with a location in the same scene as the roller-coaster ride and might thus have a stronger effect than binocular disparity on whether visual processing happens in presence or picture mode.

Our results of the verbal cybersickness ratings and the SSQ scores provide support for the first prediction. The higher cybersickness scores of the intermediate conditions as compared to the 2D screen condition ([BD = 0, MP = 0]) indicates that the visual flow might have been interpreted as self-motion which conflicted with the absence of expected corresponding input from the vestibular system. In terms of the two perceptual mode theory (Troje, 2019), the additional depth information provided by motion parallax or binocular disparity might put participants "half way" between picture mode and presence mode. Since we do not assume a linear, continuous transition between these perceptual modes, the results could be caused by repeated switches between the two modes. Over the course of the roller coaster ride, participants might have experienced less vection overall, namely only when they were in presence mode, which would have led to less conflict with the absence of registered motion by the vestibular sense and thus lower experienced cybersickness compared to the window condition.

Contrary to our second prediction, our results did not reveal any differences between the intermediate conditions in terms of verbal sickness ratings and SSQ scores. A critical difference that distinguishes motion parallax from binocular disparity as a depth cue, is that the information obtained from motion parallax is heavily dependent on the user's active movements which is not the case for binocular disparity. A possible explanation for why we did not find a difference between the intermediate conditions is that in our experiment there might not have been a sufficient amount of motion parallax. Participants were standing upright and were not actively moving around. Natural body sway is usually in the order of 1-2 cm (Era and Heikkinen, 1985) and might have been slightly higher during the roller-coaster ride. While body sway and head rotation provided micro-parallactic information, the amount of displacement was likely smaller than the inter-pupillary distance which is around 6.3 cm for adults (Dodgson, 2004). The fact that the micro-parallax induced by the much smaller body sway still induced the same increase in cybersickness as the much larger distance between the two eyes might reflect the more important role of parallax over binocular disparity in transporting the observer from picture mode into presence mode. Future studies and different experimental setups are needed to explore the effect of larger parallax on cybersickness.

Participants' EDA increased during the course of the roller-coaster ride in all four conditions equally and did not reflect the differences in cybersickness demonstrated by the subjective ratings. The increase in EDA might have been dominated by the arousing nature of the experiment rather than increases in cybersickness. Participants experienced an exciting roller-coaster ride regardless of the experimental conditions. This excitement might have masked the effect of cybersickness on the EDA results. These results question the reliability of EDA responses as a measure of cybersickness in highly arousing scenarios (also see Eftekharifar et al. (2019); Bachmann et al. (submitted) who found that EDA is also not reliable to measure presence in VR).

5. Conclusion and Future Directions

In summary, this study provides insights into the role of two prominent depth cues, motion parallax and binocular disparity, in cybersickness. Our results of the questionnaire scores and the verbal ratings showed that cybersickness increased most when the roller-coaster ride experienced in virtual reality was viewed through a simulated window, as indicated by normal stereo cues and motion parallax, and increased least when it was viewed on a simulated 2D screen. In the intermediate conditions where the Alberti Frame behaved like a window with respect to one depth cue and like a 2D screen with respect to the other, cybersickness scores ranged at an intermediate level. The results of the subjectively perceived cybersickness (verbal and SSQ scores) were not reflected in the EDA data. This suggests that EDA might not be a good proxy to measure cybersickness in VR, especially in highly arousing situations such as a roller-coaster experience. Future studies and different experimental designs are needed to evaluate the reliability of participants' EDA or other physiological and behavioural metrics (e.g., heart rate, breathing rate, respiratory volume, eye blinks, and body sway) as objective measure of cybersickness in less arousing virtual environments.

While many studies have shown a positive correlation between the extent of illusory self-motion and the amount of cybersickness, their relationship is a matter of debate (Keshavarz et al., 2015). Our results suggest that the higher rates of cybersickness in the intermediate and the window conditions are likely due to experiencing illusory self-motion. An interesting future study that could further enrich the literature of cybersickness in VR and shed more light on the relationship between these vection and cybersickness, is to investigate the effect of motion parallax and binocular disparity on both illusory self-motion and cybersickness in a similar context.

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The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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