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# You're in for a Bumpy Ride! Uneven Terrain Increases Cybersickness While Navigating with Head Mounted Displays

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## Abstract

Cybersickness (i.e., visually induced motion sickness) serves as a significant obstacle to the usage and broader adoption of virtual reality (VR) technologies. This collection of symptoms akin to motion sickness can be impacted by different characteristics of a virtual experience, such as visual realism and optical flow. However, relatively little is known regarding how cybersickness is influenced by traversing uneven virtual terrain. In this study, we aim to better understand the impacts of different virtual terrain types on cybersickness in VR. We recruited 38 participants to navigate a virtual forest environment with three terrain variants: flat surface, terrain with regular bumps, and irregular terrain generated from Perlin noise. We collected cybersickness data using the Fast Motion Sickness Scale (FMSS) and Simulator Sickness Questionnaire (SSQ) in addition to galvanic skin response data. Our results indicate that users felt greater levels of cybersickness in the presence of regular bumps and irregular terrain than they did when traversing flat geometry. We recommend that designers exercise caution when incorporating uneven terrain into their virtual experiences, and maintain awareness of the risks carried by these design decisions.

**Index Terms:** H.5.1 [INFORMATION INTERFACES AND PRESENTATION (e.g., HCI)]: Multimedia Information Systems—Artificial, augmented, and virtual realities;

## 1 Introduction

Widespread availability of head mounted displays (HMD) has opened doors into numerous commercial software applications and research opportunities. VR technologies have been used for a diverse range of applications, from the remote piloting of drones [45], to new avenues in workplace training [16], to the treatment of phobias [5], influencing dreams [17] and a growing number of games and entertainment products. HMDs have also expanded opportunities in notoriously difficult fields of research, such as understanding human behavior with respect to evacuation routes [29]. Unfortunately, VR usage can be marred by a host of negative symptoms akin to motion sickness. This collection of symptoms is referred to as cybersickness, and can prevent users from partaking in the many opportunities VR stands to offer them.

Numerous researchers have proposed augmentations to virtual environments that serve as cybersickness reduction techniques. This can involve the blurring of the screen [6, 36, 39, 30], reductions to field of view [21, 25], and more. Hardware solutions in the form of secondary wearable devices [44, 31] have also been employed. Some approaches to reducing cybersickness alter the underlying design of the virtual environment itself, which includes method of locomotion [18, 9], the graphical realism [11, 38], and the density of virtual objects surrounding the user [19]. These findings may serve as useful guidelines to designing virtual environments such that they are less prone to inducing cybersickness.

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However, little is known regarding the impacts of traversable geometry on cybersickness. In one of the few investigations on this topic, Dorado and Figueora [13] were able to reduce cybersickness by placing an invisible ramp over a virtual staircase to smooth the user's climb and descent. It is well known that virtual reality environments can expose users to irregular or obstacle ridden terrain prone to displace their position. Some of the most popular VR games such as Minecraft, Skyrim VR, and No Man's Sky all expose users to irregular terrain, but it is not known how to best shape the terrain to minimize cybersickness.

In this study, we aim to better understand how different types of virtual terrain impact cybersickness. Subjects were recruited to navigate a virtual forest with three different terrain variants: flat surface, terrain with regular bumps, and irregular terrain generated from Perlin noise. Participants navigated the environment with each terrain type in counterbalanced order while verbally reporting their level of sickness using the Fast Motion Sickness Scale (FMS) [23], and reporting their symptoms through the Simulator Sickness Questionnaire (SSQ) [22] immediately after each trial. The participants' galvanic skin response (GSR) was also collected as a physiological metric. Navigation was accomplished through a steering metaphor, where velocity was determined via input on a handheld controller – a metaphor commonly used in many commercial VR games.

Results from subjective metrics indicated that participants felt greater levels of cybersickness during their experiences with the two uneven terrain conditions. Results from the FMS showed a trend for discomfort to steadily increase over the duration of each individual trial. We were not able to detect any significant differences between the two uneven terrain types presented in our study. We expect that the knowledge gained from this study will help virtual environment designers create spaces less prone to evoking cybersickness.

## 2 Background

This section reviews the existing research towards reducing cybersickness, both through augmentations to the VR experience and through design principles applicable for the creation of virtual environments. Among the existing literature, there has been minimal research regarding the effects of traversable geometry, such as irregular terrain, on cybersickness.

### 2.1 Theory on Cybersickness Causes

Users experience cybersickness through a variety of undesirable symptoms such as nausea, disorientation, sweating, headache, and more [27]. There are competing theories as to why cybersickness exists as a phenomenon, such as the sensory conflict theory, poison theory, and postural instability theory [10]. These theories each purport different underlying causes for cybersickness. The sensory conflict theory asserts that cybersickness is the result of a contradiction between the perceived stimuli and physical motion. The poison theory suggests that the desire to vomit in the presence of visual distortions may have helped humans to survive the intake of the dangerous foods responsible. The postural instability theory places responsibility on the human body's perpetual inclination to maintain its balance.

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## 2.2 Cybersickness Reduction Techniques

With the various competing explanations in mind, researchers have developed a variety of strategies for combating cybersickness in VR environments. Some strategies are software based, utilizing image manipulation techniques such as image blurring [6, 36, 39, 30], and depth of field [8, 20]. Other common software techniques include the use of virtual rest frames [7, 3], and reduction of user field of view (FOV) [21, 25, 15]. These techniques are flexible in their capacity to augment existing virtual experiences, allowing them to remain mostly unaltered beyond the introduction of the visual effect. Unfortunately, these techniques can also be disruptive as they block out or manipulate portions of the user's vision, thereby distracting the user or blocking vital information. This has led researchers to create variants of existing techniques that minimize intrusiveness. Nie et al. [36] applied blurring effects to the users vision while leaving important salient objects such as road signs unaffected. Cao et al. [7] explored the use of dynamic rest frames that fade out of view when not needed. A user's field of view can be modified with filters that expand and retract in correspondence to content that risks increasing cybersickness [46, 42]. These dynamic approaches ideally provide relief when needed without unnecessary interruption.

Hardware approaches to reducing cybersickness offer alternatives without relying on visual distortions. These approaches can involve the use of head-bound stimulatory devices [44, 41, 31], or motion platforms [34, 35]. While these devices do not interfere with the visual content of the experience itself, they would need to be purchased separately by users, or built into the head mounted display itself to be utilized.

Other approaches to reducing cybersickness are more integrated with the virtual experience from a design standpoint. Alternative movement metaphors such as teleportation [18, 32] have been implemented to reduce cybersickness. Teleportation metaphors involve moving the user from one position to another within the simulation instantaneously, or over an extremely brief period of time. While such movement methods are useful for mitigating cybersickness, they may not be appropriate for all applications, and may impact the users' feeling of immersion within the simulation [4]. Some authors have examined design principles with regards to the virtual environment itself, such as the effects of virtual object density [19], or graphical realism [11, 38]. In this paper, we examine the impact of an environment's traversable geometry.

## 2.3 Cybersickness from Traversable Geometry

A study by Dorado and Figueroa [13] compared the effects of traversing virtual stairs against those of traversing stairs with an invisible virtual ramp placed on top to smooth navigation. To the best of our knowledge, this study represents the only inquiry into the effects of traversable geometry on cybersickness with use of a modern head mounted display (HMD). In a within-subjects experiment with 44 participants, users were asked to navigate up and down a virtual staircase in a Tuscany villa scenario. Participants completed their task using two different speed mappings, one in which movement speed was directly mapped to the position of a gamepad joystick, and another where speed was constant. After navigating up and down the stairs continuously for 2 minutes, participants filled out a SSQ to report their symptoms. Results indicate that the invisible ramp condition was significantly less prone to cybersickness ($p = .009$), for which participants had an average total SSQ score of 28.13 (SD = 26.13) compared to an average score of 74.23 (SD = 59.57) for stair geometry. This study examined a highly specific comparison between virtual stairs and ramps. Virtual stairs cause repetitive vertical displacements in the user's position and viewpoint. Ramps provide a smooth, continuous increase the user's height during traversal. However, both approaches provide little opportunity for user-determined navigation.

Our study aims to further examine the effects of traversable geometry on cybersickness, both with respect to regular and irregular displacements in user height. Our trials also take place in a more spacious and open virtual environment than the one used by Dorado and Figueroa [13] that allows users to more freely navigate their surroundings.

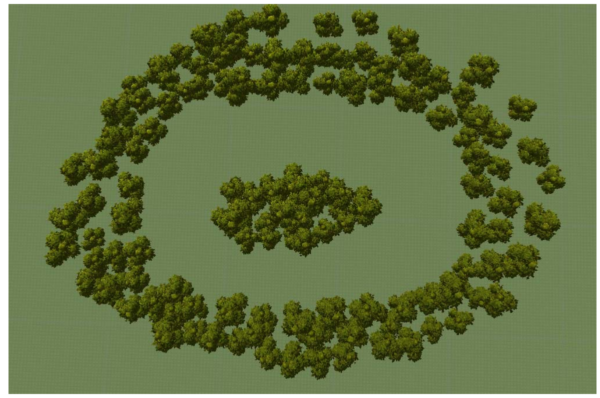

Figure 1: A bird's eye view of the virtual testing loop.

# 3 Methods

To determine the effects of terrain on cybersickness, we conducted a within subjects study with 38 participants. There were 3 terrain conditions presented in counterbalanced order. In this section we describe the design, implementation, and execution of the experiment in detail.

## 3.1 Task

While immersed in VR, participants travelled around an oval shaped path in the middle of a virtual forest. Participants stood in a designated position in physical space and used two VIVE handheld controllers to move through the virtual environment. Navigation was accomplished using a steering metaphor, where the left controller touchpad controlled velocity, and the right controller pad adjusted forward direction. Virtual facing direction was also controlled by where the test participant was looking with the HTC Vive. Users could use the right controller to turn at a maximum rate of 45 degrees per second, and reach a top speed of 4 m/s (almost nine miles per hour). This movement speed is faster than natural walking speeds of 1.44 m/s [40]. There were two motivations for using a faster movement speed. First, a higher movement speed increases the chances that users will experience cybersickness within the simulation [26]. We wanted to ensure that our simulation was capable of producing discomfort in participants so that we could compare them across conditions. Second, movement speeds within VR games and applications have the potential to be much higher than natural walking speeds. Agić et al. [1] conducted a study on different navigation speeds using the HMD game The Talos Principle VR. This game classified a movement speed of 4.25 m/s as "slow," compared to a "medium" speed of 6.37 m/s and a "fast" speed of 8.5 m/s.

## 3.2 Conditions

Participants travelled around the path through three terrain conditions in counterbalanced order for up to five minutes each. These three terrain conditions were: flat surface, terrain with regular bumps, and irregular terrain generated from Perlin noise. Figure 2 shows each terrain type from the user's perspective. We explain each of these terrain types in detail below.



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#### 3.2.1 Flat Surface

The flat surface terrain variant serves as a baseline condition. The ground is completely level and free of obstructions beyond the trees meant to guide the user.

#### 3.2.2 Terrain with Regular Bumps

This terrain variant features evenly spaced bumps obstructing the user. These bumps were placed approximately 10 meters apart within the simulation, and stood 1 meter high. The regular nature of these bumps was meant to imitate the regularly disruptive nature of stairs examined by Dorado and Figueroa [13], and see if effects persisted in an open environment with greater freedom.

#### 3.2.3 Irregular Terrain Generated from Perlin Noise

This condition served as an irregular counterpart to terrain with regular bumps. Irregular terrain is a common natural phenomenon in outdoor environments, but its effects on cybersickness within the context of VR with a HMD have not been studied to our knowledge. This irregular terrain was generated using Perlin noise [37], and seeded so that every participant completed their navigation task with the exact same terrain layout. The distance between the tops of peaks and bottoms of valleys in this condition was approximately one meter. The frequency a user would encounter these peaks was highly dependent on their chosen path through the environment. Peaks were approximately five meters apart assuming the participant travelled in a straight line.

### 3.3 Virtual Environment Layout

The virtual testing space as depicted in Figure 1 was shaped in a loop that users could walk around endlessly. We wanted to ensure that users could traverse the environment uninterrupted for a duration of five minutes. This time period was chosen to increase the likelihood that users would feel some degree of sickness by the time they were done with each trial. We considered two alternative environments layouts to achieve this goal: a wide open space with endlessly spawning points of interest for the user to navigate towards, and an endlessly linear path that dynamically spawned obstacles and environment objects as the user progressed. We had concerns that a wide open space with dynamic waypoint creation might create confusion for users unable to spot the waypoints as they spawned. An endlessly linear environment may have been too simple to navigate, allowing participants to hold down a forward button with minimal consideration. We chose a simple loop over an irregular shape so that the environment was easier to explain and conceptualize prior to the beginning of the trials.

### 3.4 Hypotheses

We made two hypotheses regarding the outcome of our experiment.

- H1: Both the terrain with regular bumps, and terrain generated from Perlin noise will increase cybersickness compared to the flat surface condition.
- H2: Terrain generated from Perlin noise will increase cybersickness compared to terrain with regular bumps.

Hypothesis 1 was made because both conditions with uneven terrain may be more likely to create postural instability due to the vertical displacement of the user. Postural instability has been used to predict cybersickness in the past [2]. Hypothesis 2 was made because the terrain with regular bumps features periods of travel over a flat surface in between bumps. In the Perlin noise condition, the user was almost always traveling on an incline. The interruptions from regular bumps may also have been more predictable to the user than irregular noise. Lack of predictability has been studied as a contributor to cybersickness [33, 12], but to our knowledge only in conjunction with denying the user control over their movement.

### 3.5 System Description

The simulation for this study was built in the Unity game engine. Participants used the 2019 HTC Vive Pro Eye to view their surroundings and the included controllers to navigate. The simulation was run on an HP Omen laptop running Windows 10 with an AMD Ryzen 7 4800H processor, a NVIDIA 1660ti graphics card, and 16 GB of RAM.

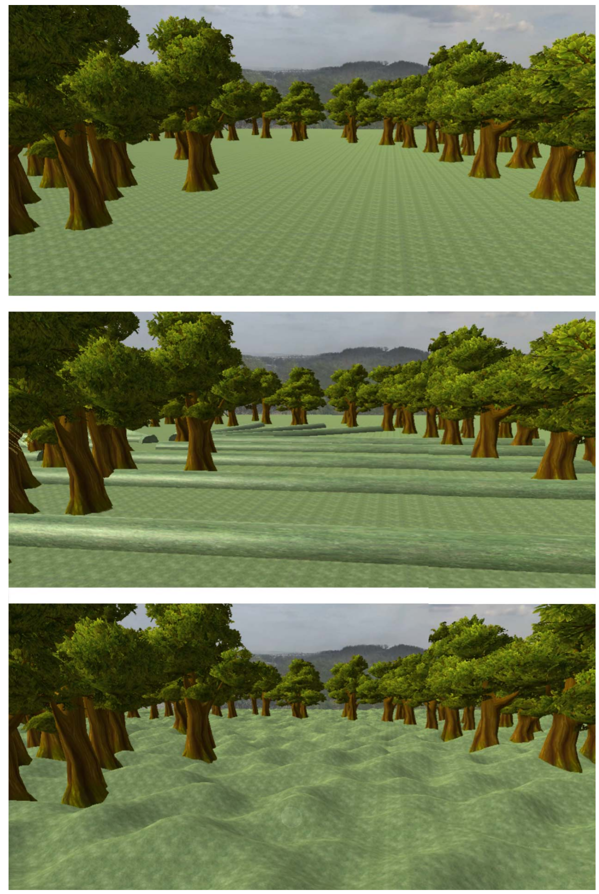

Figure 2: Depiction of the three terrain types, flat (top), regular bumps (middle), noise generated (bottom).

### 3.6 Pilot Study

We conducted a pilot study with four participants to test for issues with our study design. One participant found the navigational task confusing upon first entrance to the virtual environment. After receiving an explanation with a diagram of the environment the participant had no trouble navigating the loop. This explanation and diagram were incorporated into the study to provide clarity. Another participant reported seeing graphical glitches in the branches of the virtual trees during their run. These trees were replaced with less detailed models to address this issue. Two participants expressed confusion over the control scheme. An additional explanation of the controller touch pads was introduced prior to participants putting on their headsets to address this issue. One participant had their digital questionnaire reset due to a tablet screen timeout. Screen timeout was disabled for future data collection. Two pilot participants were unable to begin a third trial due to high levels of sickness.



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### 3.7 Power Analysis

We conducted a one-way ANOVA F test to determine the necessary number of participants for this study. We did not use the data from our pilot study for this calculation because two participants were unable to complete all three trials. Because there was little research on the effects of traversable geometry on cybersickness, we used the results of Dorado and Figueroa [13] to estimate the effect size of different terrain types. Using these results with the G*Power statistical analysis tool [14], we calculated that the effect size (Cohen's D) of ramps compared to stairs in this study was calculated to be .57. We used this effect size as an estimate for our study. With the three conditions of our study, a within-subjects design, and an error probability of 0.05, we calculated that a sample size of 33 participants would be necessary to achieve a power level of 0.8.

### 3.8 Population

We recruited 40 participants via an online signup sheet. Data from two of these participants was not included in our results. One individual quit early due to high levels of sickness during the first of three trials, and a second was unable to stand for the duration of the experience. Of the remaining 38 participants, there were 17 women, 20 men, and one individual who identified as non-binary. The age of participants ranged from 18 to 65. Mean age was 34.83 years old with a standard deviation of 13.20 years. Of our 38 participants, 26 identified as white, 7 as hispanic, 6 as Asian, 2 as American Indian, and 2 as African American. Note that participants were allowed to select multiple ethnic categories to describe themselves. Participants were paid $35 an hour for their time and effort.

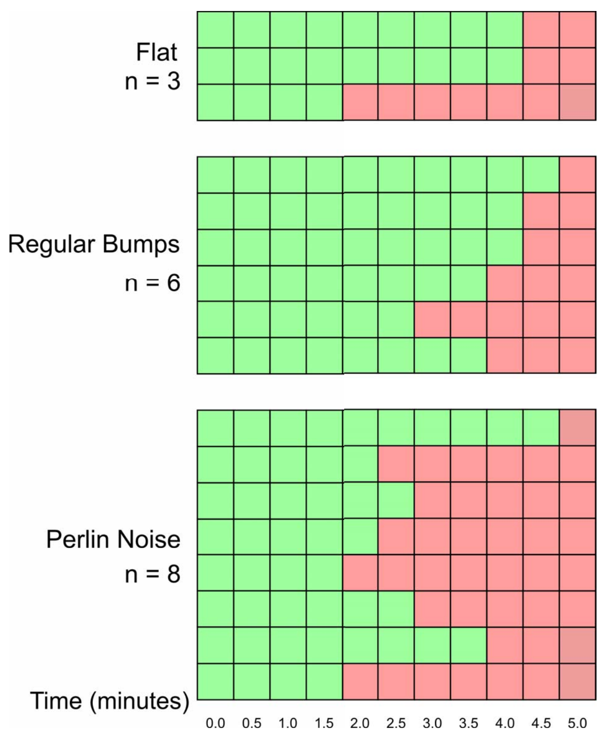


Figure 3: Participant premature trial termination across all three conditions. Squares marked in red represent timestamps post dropout.

### 3.9 Study Procedure

An outline of the study procedure is illustrated in Figure 4. The study took approximately 45 minutes to complete. Participants began by filling out a background information questionnaire and preliminary SSQ [22] to gauge their level of sickness prior to the beginning of the experiment.

Participants were told that they could end the test at any point if needed. Nine participants asked to end one or more of their trials early. This resulted in three early terminations during the flat condition, six during the regular bumps trial, and eight during the Perlin noise trial. Information on the time of these dropouts is shown in Figure 3. Next, participants were instructed on the navigation task and shown an overhead diagram of the virtual testing area on a whiteboard. Participants were then given a position to stand, fitted with an HTC Vive Pro Eye, given accompanying handheld controllers, and fitted with the E4 wristband on their non-dominant wrist. Participants were given a brief explanation and opportunity to test out the navigation system in the flat terrain setting. Then, participants travelled in the loop across all three terrain types in counterbalanced order for 5 minutes each. After each trial, participants filled out a SSQ, and took a 1 minute break. This break was extended one minute at a time until participants reported a FMS of 1.

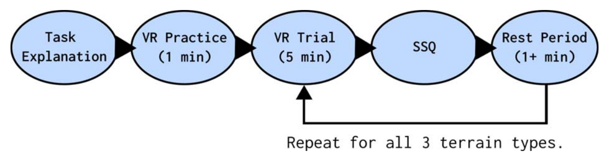


Figure 4: Outline of study procedure.

### 3.10 Metrics

We collected cybersickness data throughout the study using three metrics.

- FMS [23] is a verbal rating of level of discomfort from 1(none) to 10(severe) [24]. Starting at the beginning of a condition, we asked participants to report FMS every 30 seconds during VR exposure and once per minute while resting in between conditions.
- SSQ [22] is a written questionnaire consisting of 16 items (e.g., sweating, nausea) that are rated on a scale of 0(none) to severe(3). From this data, three subscores can be calculated for nausea-related, oculomotor-related, and disorientation-related. From these three subscores, a total score is calculated, representing the overall severity of cybersickness experienced by the participants.
- GSR. The Empatica E4 Wristband was attached to the participant's wrist at the beginning of the study to collect GSR data. The wristband recorded four ratings each second.

### 3.11 Data Processing and Statistical Analysis Overview

For the duration of the study, participants wore an Empatica E4 wristband to collect data on GSR. For each participant, we took the measured response at the beginning of each trial as a baseline for the condition, and subtracted it from the subsequent data collected for that condition. We then took the data and averaged them to create an overall GSR for each participant for each condition. These overall GSR were used in our final analysis.

A preliminary SSQ was given to participants before they entered VR. Total SSQ scores from this initial questionnaire were minimal (M = 4.62, SD = 6.36) with no participant exceeding a total score of 22.44. Subsequent SSQ scores across all symptoms were adjusted by subtracting preliminary scores before analysis took place.

Each data source (i.e., FMS, SSQ, GSR) was tested with a Shapiro-Wilk test to determine normality. Because each was found



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to be non-normal, we decided to conduct non-parametric Friedman tests followed by post hoc Wilcoxon Signed-rank tests for analysis. The reported p-values of the Wilcoxon tests were Bonferroni corrected for multiple comparisons.

## 4 Results

In this section we report our findings from participant FMS, SSQ, and GSR.

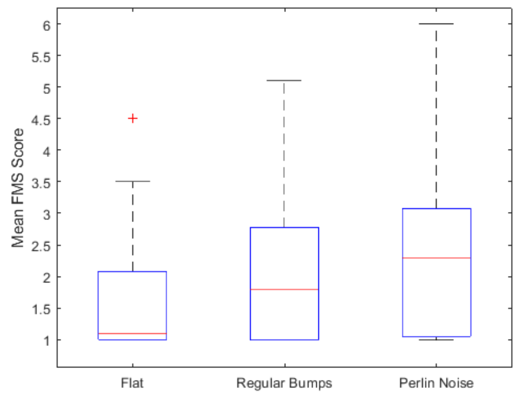


Figure 5: Box plot of mean FMS across conditions.

### 4.1 FMS Results

For each participant, we computed overall FMS scores by averaging their responses during each condition. This gave us three values per participant, each describing their experience with a different terrain type. We additionally collected the maximum FMS score reported by each participant over the course of each trial. For our analysis of mean and maximum FMS scores, we removed outliers by conservatively omitting two participants with overall scores more than three median absolute deviations from the mean of the group [28]. This left us with data from 36 participants. A Shapiro-Wilk test determined that the data for both maximum (p = 3.604e-05), and mean FMS (p = 1.751e-06) scores were not normal.

The mean overall FMS rating for the flat terrain experience was the lowest (M = 1.58, SD = .90) followed by that of the terrain with regular bumps condition (M = 2.08, SD = 1.22) and finally by that of the terrain from Perlin noise (M = 2.38, SD = 1.36). A Friedman rank sum on the overall FMS scores indicated that terrain type had a highly significant impact ($p < .001$), allowing us to reject the null hypothesis. A corrective Bonferroni post hoc Wilcoxon signed-rank test revealed significant differences between scores of participants in the flat terrain, and Perlin noise conditions (V = 10.5, $p < .001$, Cohen's d = .693). Differences between flat terrain and the regular bumps conditions (V = 44, p = 0.023, Cohen's d = .462) were also significant. No significant differences were found between regular bumps and Perlin noise conditions (V = 93.5, p = .115, Cohen's d = .235).

We plotted the mean FMS scores over time for each condition up to the four minute timestamp. These plots can be found in Figure 6. We omitted the scores of five individuals who asked to end one or more of their trials prior to four minutes. Full information on early terminations for each condition are shown in Figure 3.

Analysis of maximum FMS ratings returned similar results to the mean FMS. Flat terrain maximum FMS scores were once again the lowest (M = 2.19, SD = 1.70) followed by terrain with regular bumps (M = 2.97, SD = 2.13) and finally by those of terrain from Perlin noise (M = 3.42, SD = 2.30). Data from the same two outliers

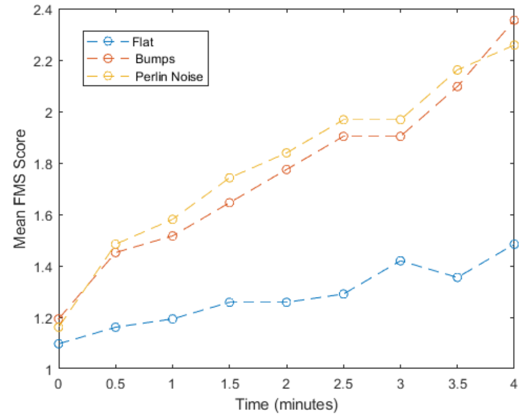


Figure 6: Mean FMS scores for each timestamp from zero to four minutes.

| FMS Measure | Flat | Regular Bumps | Perlin Noise |
|---|---|---|---|
| **Mean Score** | 1.58 ± 0.90 | 2.08 ± 1.22 * | 2.38 ± 1.36 * |
| **Mean Max Score** | 2.19 ± 1.70 | 2.97 ± 2.13 | 3.42 ± 2.30 * |

Table 1: Reported FMS scores for each terrain type. Values significantly different from those in the flat condition are marked with *

was omitted, leaving us with results from the same 36 participants. A Friedman rank sum test once again revealed a significant impact of terrain type on these scores ($p < .001$) and a Bonferroni post hoc Wilcoxon signed-rank test attributed this to a difference between flat and Perlin noise conditions (V = 25, p = .003, Cohen's d = 0.604). Differences between flat terrain and the regular bumps conditions (V = 65, p = .074, Cohen's d = .403) and between the regular bumps and Perlin noise conditions (V = 64 , p = .104, Cohen's d = .201) were not significant.

### 4.2 SSQ Results

After each individual VR condition, participants rated their symptoms post exposure by filling out an SSQ. We subtracted the scores of the preliminary SSQ questionnaires from these and used the resulting scores for our final analysis. The data of two outliers was omitted from consideration. These outliers were identified based on their SSQ total scores lying more than than three median absolute deviations from the group as before [28], leaving us with data from 36 participants. The mean scores of the remaining participants are listed in Table 2. We first performed a Shapiro-Wilk test to check the normality of the data. We found that the nausea (p = 0.003), ocularmotor (p = 0.028), disorientation (p = 0.002), and total scores (p = 0.020) were not normally distributed.

Through performing Friedman ranked sum tests we detected a potentially significant impact of terrain type on nausea (p=.003), oculomotor (p=.028), disorientation (p=.002), and total scores (p=.020).

With regards to total SSQ score, a post hoc Wilcoxon signed-rank test with Bonferroni correction found significant differences between flat and regular bumps condition (V = 89.5, p = .030, Cohen's d = .387) and between the flat and Perlin noise conditions (V = 140.5, p = .038, Cohen's d = .370), with no significant difference between regular bump and Perlin noise conditions (V = 287 , p=1, Cohen's d = .042).

Significant differences were not found between the nausea subscores of the flat and Perlin noise conditions (V = 122.5, p = .072, Cohen's d = .363), flat and regular bumps scores (V = 86.5, p =



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| SSQ Score | Flat | Regular Bumps | Perlin Noise |
|---|---|---|---|
| **N** | 15.15 ± 19.81 | 28.34 ± 28.33 | 28.34 ± 20.27 |
| **O** | 5.57 ± 13.63 | 12.04 ± 14.23 | 9.14 ± 13.69 |
| **D** | 18.83 ± 26.07 | 30.71 ± 28.00 | 31.12 ± 34.45 |
| **TS** | 13.75 ± 19.22 | 23.50 ± 22.72 * | 23.98 ± 19.47 * |

Table 2: Reported SSQ nausea (N), oculomotor (O), disorientation (D), and total (TS) scores for each terrain type. Values significantly different from those in the flat condition are denoted by *

.072, Cohen's d = .307) or between regular bumps and Perlin noise conditions (V = 221, p = 1, Cohen's d = .019).

Our post hoc tests failed to confirm any significant findings for oculomotor subscores between flat and regular bumps conditions (V = 57.5 ,p=.077, Cohen's d =0.390), flat and Perlin noise conditions (V = 58.5, p=.145, Cohen's d = .213), and regular bumps and perlin noise conditions (V = 169, p=1, Cohen's d = .184).

Differences in disorientation subscores between flat and regular bumps conditions (V = 90.5, p=.093, Cohen's d = .357), flat and Perlin noise conditions (V = 120, p=.179, Cohen's d = .333), and regular bumps and Perlin noise conditions (V = 147, p = 1, Cohen's d = .0126) were not significant.

### 4.3 GSR Results

We were unable to collect data from three participants due to apparatus failure. Data from an additional four participants were omitted as outliers with overall scores more than three mean average differences from the mean. This left us with data from 31 participants. The highest mean overall GSRs were collected from the regular bumps condition (M = 1.38$\mu$s, SD = 3.39) followed by those in the Perlin noise condition (M = 1.14$\mu$s, SD = 2.08) and finally those from the flat condition (M = .87$\mu$s, SD = 2.16). Using a Shapiro-Wilk test, we found that GSR was not normally distributed (W = .69, p = 1.238e-12). A subsequent Friedman rank sum test did not find a significant difference in GSR (p = .51).

## 5 Discussion

In this section we discuss the results of our experiment and their implications. Observations regarding the participants' behavior, and the limitations of our study are also addressed here.

### 5.1 SSQ Discussion

From our SSQ scores we were able to confirm our first hypothesis, that the both regular bumps and Perlin noise conditions resulted in increased levels of reported cybersickness compared to flat terrain. These results support the findings of Dorado and Figueora [13] in their comparison of ramps and stairs. In both studies, participants felt greater levels of cybersickness when traversing uneven geometry compared to a flat surface. Our results indicate that uneven terrain can present risks in broader use cases outside of climbing larger slopes or staircases.

We were unable to verify hypothesis 2 with our results. Participants reported similar levels of sickness between regular bumps and Perlin noise conditions, particularly on the SSQ where both nausea scores and total scores were nearly identical. It may be that the periods of flat terrain between regular bumps were not long enough to mitigate the discomfort from crossing an interruption. We previously mentioned how the predictability of the regular bumps condition may also result in reduced cybersickness. However, predictability, to our knowledge, has only been studied in conjunction with affordance of control [33, 12, 43]. It may be the case that reduced predictability does not impact cybersickness when users are in full control as they were in our experiment. Alternatively, it may be the case that the Perlin noise condition was no less predictable than the regular bumps condition because participants could observe and choose a path in front of them.

Existing research presents at least three explanations for these results: sensory conflict, postural instability [10], and predictability [33, 12, 43]. Uneven terrain variants may increase postural instability as users are forced to contend with inclines missing from the flat terrain variant. These vertical irregularities may also exacerbate conflict between the users' physical and perceived motion. The physical elevation of participants does not change during each experience, but uneven terrain variants introduce the perception of vertical displacement in virtual space. Finally, uneven environments may result in unpredictable motions during traversal. As mentioned before, we are only aware of studies examining predictability with regards to affordance of control [33, 12, 43]. Further research is needed to understand the impacts of other factors that affect predictability.

### 5.2 FMS Discussion

Results from FMS ratings similarly confirm our first hypothesis. Results from FMS reports indicated a significant difference between overall and maximum scores between flat and Perlin noise conditions, but not between flat and regular bumps conditions. Plotting the mean scores for each time step revealed a close similarity between the reports of participants in the regular bumps and Perlin noise conditions over time. FMS ratings tended to gradually increase for all three conditions, but at a lower rate for the duration of the flat terrain experience. The similarities between the reports of regular bumps and Perlin noise conditions warrant further investigation. The irregularity of the Perlin noise terrain did not result in a marked increase in FMS during our experiment, but may do so under different circumstances.

### 5.3 GSR Discussion

We did not uncover any significant findings from GSR readings. A potential explanation for this is an insufficient waiting period between each trial for participants. From examining individual readings, we observed a tendency for GSR to increase for the duration of each VR experience, and then decrease during the following waiting period. As mentioned previously, we ensured that participants reported a minimum discomfort rating on the FMS before ending each break, but this did not ensure that GSR fell to nominal levels before resuming VR activity. From reading the recorded history of the ratings we discovered that many participants began their second or third VR trial while GSR was still falling, thus potentially distorting our results. Future research could be bolstered by additional physiological metrics such as heart rate.

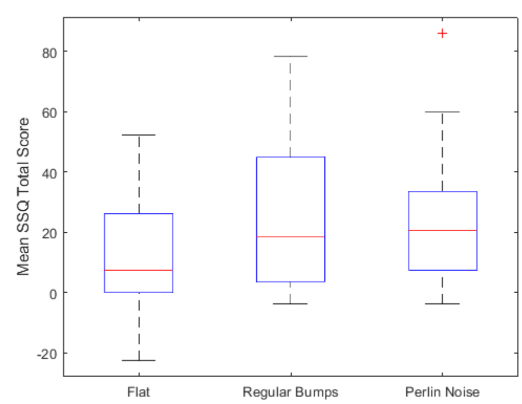


Figure 7: Box plot of mean SSQ total scores across conditions.



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### 5.4 Observations

During each trial, we took notes on the reactions and comments made by participants. We did not instruct participants to provide verbal feedback, but allowed it if they chose to do so. Several participants expressed feelings of boredom during their experience with flat terrain, and feelings of excitement and interest when traversing uneven terrain. Participants often described uneven terrain types as "fun," or even "hilarious." While these terrain types appear to have negative impacts on cybersickness, even rendering the experience intolerable for a small subset of users, we hypothesize that they may be more stimulating or entertaining for users to interact with. Some participants, particularly during the start of the Perlin noise condition, expressed feelings of nervousness or intimidation. Immediately after moving across uneven terrain, participants almost universally expressed that the change in vertical position felt unnatural, strange, or confusing. These comments typically subsided as the experience went on, possibly due to participants acclimating to the feeling.

### 5.5 Limitations

Our study is limited by a number of factors and design choices. Firstly, the design of our experiments only kept participants immersed in the simulation for at most five minutes at a time. When using VR applications for education, social interaction, or entertainment; individuals may require much longer periods of exposure. Each five minute period also contained a singular terrain type for the entire duration. Brief encounters with disruptive terrain on otherwise flat geometry may not impact cybersickness in a longer VR experience. Future research is required to understand longer scenarios with mixed terrain more akin to existing VR applications. The brief waiting period between each trial may have also impacted our results. Though we waited until participants reported an FMS rating of one before reinserting them, other factors contributing to cybersickness may have carried over to subsequent trials.

Another limitation of this study is the maximum movement speed of 4 m/s. As mentioned previously, this speed is much greater than natural walking speeds [40], and VR games can allow users to travel faster [1]. Users may not experience the same negative outcomes we observed when traveling over uneven terrain with a different movement speed. Further research is needed to understand the interaction between movement speed and traversable virtual terrain.

We offered participants the freedom to choose their pace and route through the environment. In doing this, we did not standardize the distance travelled, nor the number of pauses participants took during their journey. As a result, the unique experiences of each user may have impacted our results. In future work, we hope to analyze how terrain type impacts user movement patterns.

The terrain types selected for our study only vertically displaced users by approximately one meter in the simulated world. Large hills and mountains within a simulation would displace users a greater distance over a longer period of time, and small deformations in the geometry could displace users by far less than what was experienced in our simulation. We chose the two terrain variants to understand if the regularity of disruptions impacted cybersickness, but it is unknown how broadly applicable the results of our study are to the full range of terrain types available to designers.

Participants navigated through each trial using a steering metaphor. While this mode of control is present in many popular VR games, future research may find different results with alternative locomotion methods such as teleportation.

Lastly, our study relies on the data of only 36 participants. We recruited participants from the local area rather than from the student body of our University to broaden the representation of age groups, but it is undeniable that future work would be bolstered by a larger sample size from different regions.

## 6 Conclusion

In this study we examined the impacts of virtual, traversable terrain on cybersickness. This was done with three terrain variants, flat, regular bumps, and Perlin noise to investigate both the influence of vertical displacements and the effects of their regularity. The results of two subjective metrics, FMS and SSQ, indicated that users felt significantly greater levels of cybersickness in both conditions where terrain featured distortions. These results may be attributed to the greater levels of postural instability caused by uneven terrain types, though more research is necessary to determine the underlying reason for this phenomenon. In light of these results, we recommend that designers of virtual environments exercise caution when introducing obstacles or distortions to traversable terrain. In the future, we wish to expand our research by examining the effects of terrain in other settings, such as piloting vehicles; and examining effective methods of mitigating cybersickness in scenarios with complex terrain.

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