

# Mitigation of VR Sickness During Locomotion With a Motion-Based Dynamic Vision Modulator

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**Abstract**—In virtual reality, VR sickness resulting from continuous locomotion via controllers or joysticks is still a significant problem. In this article, we present a set of algorithms to mitigate VR sickness that dynamically modulate the user’s field of view by modifying the contrast of the periphery based on movement, color, and depth. In contrast with previous work, this vision modulator is a shader that is triggered by specific motions known to cause VR sickness, such as acceleration, strafing, and linear velocity. Moreover, the algorithm is governed by delta velocity, delta angle, and average color of the view. We ran two experiments with different washout periods to investigate the effectiveness of dynamic modulation on the symptoms of VR sickness, in which we compared this approach against a baseline and pitch-black field-of-view restrictors. Our first experiment made use of a just-noticeable-sickness design, which can be useful for building experiments with a short washout period.

**Index Terms**—VR sickness, contrast manipulation, vision modulation, shading and rendering

## 1 INTRODUCTION

VIRTUAL reality (VR) sickness, also known as cybersickness or visually induced motion sickness in virtual environments (VEs), can result in symptoms such as nausea, dizziness and vomiting, which prevent users from staying in the VE for longer periods of time and can persist even after the experience ends [35]. These unpleasant symptoms often lead to users refusing to try VR again. The most commonly accepted explanation of VR sickness is the sensory conflict theory [49], [50], which states that self-motion perceived from the view within a head-mounted display (HMD) is mismatched with the motion perceived by the human vestibular system. This eventually causes the human body to react strongly with discomfort.

To date, HMDs use advanced tracking systems and high refresh rates to prevent VR sickness for general use by eliminating the mismatch of self-motion between the user’s visual and vestibular perception when virtual head motion is intended to correspond to tracked physical head motion. However, this does not address users who wish to use a controller or gamepad to move through the virtual world,

due to a lack of physical room space or a desire to remain relatively stationary. Since the problem of locomotion in VR has not been perfectly resolved, open-space VR content has relied on various mechanisms for locomotion with controllers such as joysticks or trackpads. Frequently used techniques include teleportation, ratchet-based rotation, blurring [14], or field of view (FoV) restrictors [6], [25].

Both teleportation and ratcheting are effective for movement and diminish VR sickness by immediately transporting or transforming the user’s virtual body to a target position or orientation instead of moving it continuously. This prevents the optical flow ofvection in the user’s view in order to avoid sensory conflict. However, moving without optical flow can result in a lack of immersion [9] and may cause spatial disorientation [3], [5]. Much VR content, especially open-space VR games, makes this tradeoff, applying teleportation as its default locomotion method.

The FoV restrictor is another technique that is widely used to support controller-based continuous locomotion. It helps in reducingvection-induced VR sickness by partly reducing the optical flow in the periphery, while the user’s cognition of orientation is significantly affected. This technique, which is also known as tunneling, is commonly implemented by an opaque texture (pitch-black) with a smooth-edged transparent circle in the center of the view, sometimes dynamically controlling the radius of the FoV based on velocity [25]. Studies have demonstrated that covering visual information in peripheral vision is somewhat effective at mitigating VR sickness [8], [34].

However, decreases in the size of the FoV are correlated with decreases in the sense of presence [36], [54]. As such, it is difficult, if not impossible to find an FoV restrictor size that results both in significantly reduced VR sickness and a high level of presence [25], [52]. To overcome the drawbacks of pitch-black FoV restrictors, eye trackers have also been applied to create a foveated FoV restrictor [1], though results still did not completely solve the problem of reducing sickness while

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Fig. 1. Images showing (a) a typical virtual environment with no visual effects, (b) a black FoV restrictor designed to reduce VR sickness [25], (c) our vision modulator, which dynamically reduces peripheral contrast in response to movements that generate intersensory conflict, (d) a rendering of the view to illustrate how we modify pixel contrast with respect to depth, and (e) a spherical representation of the range of coverage of the modulator in world space.

achieving a high level of presence. In addition, blur effects have been widely explored as FoV modifiers in place of FoV restrictors with the thought that they might reduce optical flow but preserve sense of presence and immersion [14], [16], [30], [37], [42]. Though VR sickness may be reduced, blurring still does not fully block optical flow in the user’s FoV, for example for large, high-contrast objects such as pillars or corners, which can still lead to disorientation.

In this paper, we introduce a novel set of algorithms that dynamically modulate the user’s vision with a low-contrast screen effect, as outlined in Fig. 1. Simply put, our goals are to 1) reduce the amount of optical flow in the peripheral field of view, 2) do this using a shading technique that does not cause noticeable distraction and reduce sense of immersion, and 3) apply this technique only during sickness-inducing motions. To accomplish this, we have designed an algorithm that changes intensity in response to both the user’s virtual motions and the depth of pixels in world space. Specifically, the vision modulator described here is correlated with the conflicting delta velocities and angles resulting from the combination of controller-based linear motions with head rotations and translations. Moreover, instead of implementing a pitch-black restrictor, our strategy was to reproduce the coloration of the environment without generating optical flow. The color of the low-contrast effect is governed by the average color of the user’s view, sparsely sampled from pixels on the screen on a frame-by-frame basis. Our goal is to mitigate VR sickness in controller-based continuous locomotion by reducing the speed users perceive when their virtual motion changes to make the view look more stable. Our contributions in this paper are summarized as follows:

- The design, testing, and refinement of a shading technique (vision modulator) designed to reduce VR sickness and without becoming distracting by reducing optical flow, engaging only during potentially sickness-causing motions, and preserving scene coloration.
- Two experiments with different washout periods testing this modulator against a state-of-the-art FoV-modulation technique and a baseline condition, as well as analysis and discussion of the results.

In the following sections, we discuss related work, detail the design process and implementation of the vision modulator, describe experiments, and provide an analysis of the data. We conclude with a discussion of our results and observations.

## 2 RELATED WORK

VR sickness is a major problem in VR that not only stops users from long-term use, but also impedes controller-based

continuous locomotion—the easiest and least expensive travel method. This has stood in the way of wide-scale adoption of VR. In this section, we discuss various theories of VR sickness andvection perception, as well as previous proposed solutions that extended from these theories.

### 2.1 Visual Perception of Vection and Speed

Our speed of motion can be misperceived by our eyes [52] in both the real world and VR. Diels *et al.* [21] observed that speed perceived as driving forward in a driving simulator is positively correlated with FoV size. However, simply reducing FoV size may not always be effective in reducingvection, which can also be influenced by foveal visual stimulation or by eye movements [61]. In addition, Banton *et al.* [4] found that participants in a VE perceived a walking speed close to their actual walking speed when looking downward/leftward, but a lower speed when looking forward. Regarding this phenomenon, we believe that studies of visual angular velocity could explain it.

The relationship between visual angular velocity (i.e., the angular velocity of textures or objects passing through the view), distance, and relatively perceived speed has been studied by many researchers. For example, Brown *et al.* [11] observed that when the angular velocity of an object in view is decreased by decreasing the distance to it, the perceived speed of the object will decrease. Furthermore, Wist *et al.* [63] conducted experiments based on Brown’s findings, in which they tested perceived speed by a surrounding cylinder that expanded and rotated constantly, suggesting that linear velocity plays an important role along with angular velocity in the perceived speed of object-referred self-motion.

Longuet-Higgins *et al.* explained visual angular velocity by thinking of vision as a “hemispherical pinhole camera” [39] in which the pinhole is the focus point moving on the surface of the hemisphere. Therefore, they suggested that if the user is heading or gazing in a different direction than the direction of motion, both the translational and rotational components should be calculated to define relative motion. In addition, the well-known motion parallax theory describes the change of optical flow in the view that results from a change of the observer’s viewing position. This leads to a perception of motion of stationary objects during locomotion, which is correlated to “apparent angular velocity” [29]. Further studies have investigated the effect of an object’s angular velocity passing the FoV on the perception of distance and motion during locomotion [26], [45]. From a biological perspective, Ewert [24] demonstrated that increased visual angular velocity leads to increased activation of motion-sensitive neurons in the retina.

On the other hand, perceived speed is also related to contrast, as proposed by Thompson [60]. Stone *et al.* [58] observed this phenomenon in a 2-D environment and found that motion was perceived to be slower as contrast is reduced. Brooks [10] also studied this finding with binocular images moving in depth and reached the same conclusion.

## 2.2 Sickness-Inducing Motions and Motion Estimation

The widely accepted sensory conflict theory [49], [50] explains VR sickness by the mismatch of visually perceived self-motion and motion perceived by the vestibular system. With further consideration of whether users experience motion sickness whenever they locomote in real life and in simulators, the effect of “sensory rearrangement” was proposed by Held *et al.* [28]. In addition, the relationship between motion sickness produced by “sensory rearrangement” and that resulting from external motion disturbances was defined by Oman [44]. On the other hand, Perrone *et al.* [48] proposed a model defining how the human visual cortex and brain estimate self-motion in 3-D environments. In addition, this estimation works together with gaze stabilization to produce a feeling of stability as self-motion is perceived. Further studies demonstrated that motion changes that compromise the estimation of self-motion can induce motion sickness in both the real world and VEs [20]. These motion changes include change of velocity/acceleration [2], [13] and change of direction [7], [43]. Studying these motions, researchers also observed that there was a nonlinear relationship between the sickness participants felt and the visually perceived changes of self-motion. Young [65] built a model to define the nonlinear relationship of visual–vestibular interaction and proposed that there is a range of “sensory rearrangement” value to induce sensory conflict.

## 2.3 Mitigation of Controller-Based Continuous Locomotion-Induced VR Sickness

In previous studies, approaches to mitigate VR sickness induced by controller-based continuous locomotion were proposed from both visual and non-visual perspectives.

From a non-visual perspective, Russell *et al.* [53] found that paced diaphragmatic breathing training relieves VR sickness symptoms by activating the parasympathetic nervous system. Recent studies have tested physical stimuli to combat VR sickness. Weech *et al.* [62] studied whether noisy vestibular stimulation through bone-vibration could reduce VR sickness. Peng *et al.* [47] applied vibrotactile feedback to participants’ heads, significantly reducing VR sickness while improving presence in virtual walking scenarios. Based on Weech’s and Peng’s strategies, Liu *et al.* [38] developed a head-mounted air propulsion system and demonstrated that it improved realism and mitigated VR sickness in different high-speed motion simulators. Auditory approaches have also been tested. For example, Dahlman *et al.* [19] compared the effectiveness of an artificial sound horizon with non-positioned sounds and demonstrated that non-positioned sounds could be used to mitigate symptoms of motion sickness. With further studies, Keshavarz and Hecht’s [33] results showed that pleasant music reduces overall severity of visually induced motion sickness.

Compared with non-visual methods, visual methods have advantages including ease of application, no potential side effects on the body, and low cost. The most studied approach of this type is vision restrictors/modulators. Fernandes and Feiner [25] developed a dynamic FoV restrictor for HMD-based VR in which the FoV was inversely correlated to the mismatch between the user’s physical head motion and their virtual head motion. Brument *et al.* [12] conducted a study to test different types of FoV restrictors that blacken or blur the periphery during different rotation gains. Wu and Rosenberg [64] describe FoV restrictors that render a wireframe visualization of the real world geometry in the periphery to serve as a stable reference frame during virtual travel. Based on Fernandes and Feiner’s study, Adhanom *et al.* [1] developed a foveated FoV restrictor driven by eye tracking, but did not find that it significantly reduced VR sickness relative to an unfoveated FoV restrictor.

Blur effects have also been studied as an approach to mitigate VR sickness. Kieran and Rhee [16] implemented a dynamic depth-of-field modulator with blur and demonstrated that it could reduce overall discomfort in VEs while being difficult for participants to notice. Nie *et al.* [42] developed and analyzed a saliency-detection-based blur modulator for a driving simulator, demonstrating that it was effective at mitigating VR sickness. Beside FoVs, Cao *et al.* [15] demonstrated the effectiveness of static and dynamic rest frames on mitigating VR sickness. However, an additional study conducted by Zielasko *et al.* [67] contradicted the effectiveness of static rest frames. Chardonnet *et al.* [17] tested the correlation between VR sickness and navigation parameters such as gestures and distances. Lou and Chardonnet [40] proposed a geometry-deforming method to mitigate VR sickness.

## 3 DESIGN AND IMPLEMENTATION OF THE DYNAMIC VISION MODULATOR

To reiterate, our primary goals with the vision modulator were to 1) reduce the amount of optical flow in the peripheral field of view, 2) do this using a shading technique that minimizes sense of distraction and awareness, and 3) to apply this technique only during sickness-inducing motions. As such, we started by testing different blur effects, since prior work suggested that blurring might be one way to reduce VR sickness. We implemented several shaders using High Level Shading Language (HLSL) to generate these effects, such as average blur, radial blur and a bilateral filter, as shown in Fig. 2. However, practical testing of these blur effects did not show them to be effective at slowing pixel movement in the field of view (FoV). When larger objects with high contrast passed by, the

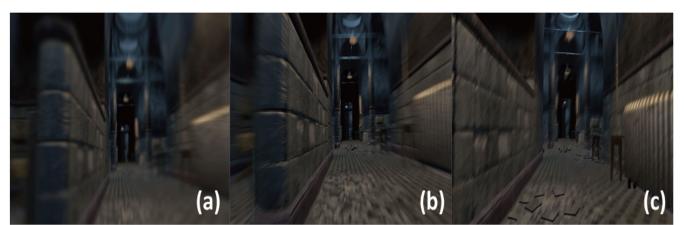


Fig. 2. Images showing the initial blur effects that we tested: (a) average blur, (b) radial blur, and (c) a bilateral filter.

frame-to-frame changes would still create significant optical flow despite any type of blurring.

Because optical flow is a result of the changing contrast of pixels, we next considered how we might be able to change contrast while still preserving scene detail. We first implemented a Unity shader that reduced screen contrast to see if this approach might have potential. The shader was attached to the main camera in the VE, which directly modifies contrast in the HMD. The next step in our design was to ensure that changes to the contrast of the FoV occurred only during actions or motions that generate VR sickness. For example, if a user is traveling at a constant velocity, there is no need to compensate for intersensory conflict, since this would be the equivalent of riding a bike or vehicle at constant speed. The real problems occur during acceleration, strafing, and combinations thereof.

Moreover, different areas of the FoV will have different angular velocities of optical flow relative to the user's motion, so we adapted the effect to process the areas that have higher visual angular velocities. Furthermore, this was triggered by motions caused by controller interaction rather than by physical head motion, including acceleration, strafing, and rotation. Finally, in contrast to black FoV restrictors, we tried to preserve scene color as best as possible by sampling pixel colors from the areas covered by the effect. This was done in an attempt to decrease the user's awareness of the effect in order to reduce the distraction it might cause.

### 3.1 Color Sampling

Our next task was to design a method that could replicate scene coloration without generating optical flow. We needed to sample screen pixels in a way that both matched the scene and ran in real time on a commodity graphics card. To accomplish this, we implemented a Unity shader that accessed a  $36 \times 36$  grid of pixel colors from the camera view (i.e., a fragment of the camera texture). These were sparsely sampled at a distance of 40 pixels to cover the entire camera view and run in real time. The number of sampling pixels was determined by trial and error while monitoring frame rate using an NVIDIA GeForce RTX 2070 graphics card.

After sampling the pixel grid, we calculated the final color using a depth-weighted average, which was calculated with the z-buffer values of every sampling pixel to ensure that the color accurately covered the scene's depth range. Then we passed the final color to the following pass of the shader, where we obtained the final color and merged it with the colors of pixels using linear interpolation (Lerp). In addition, the parameter of the Lerp was defined by applying a smooth Hermite interpolation between 0 and  $CR$  (a value that will be defined in Section 3.2) to each pixel's distance. Finally, we compared the luminance of the pixels with the average color to make the highlighted and shadowed area more visible.

### 3.2 Vision Modulator Parameters

After sampling the color for the low-contrast effect, we determined the depth range and intensity. We aimed to cover high angular velocity ( $\omega$ ) areas in the view, so we first applied the angular velocity equation (Fig. 3a):

$$\omega = (v * \sin \theta) / r. \quad (1)$$

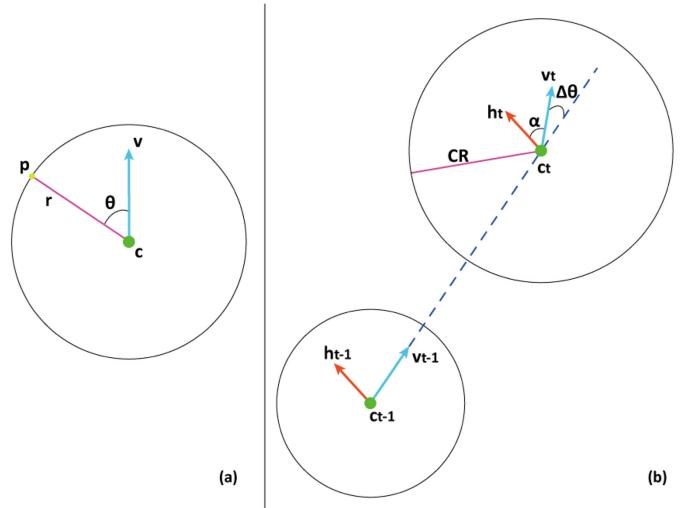


Fig. 3. (a) Calculation of the angular velocity of a pixel, where  $v$  is the linear velocity value,  $c$  is the camera,  $p$  is the pixel,  $\theta$  is the angle between the pixel's direction and linear velocity direction, and  $r$  is the distance from the camera to the pixel. (b) Parameters:  $c$  is the camera,  $t$  is the current second,  $h$  is the head direction,  $\alpha$  is the angle between head direction and linear velocity direction,  $v$  is the linear velocity value,  $\Delta\theta$  is the variation of linear velocity direction, and the circles stand for covering range ( $CR$ ).

To make the modulator triggered by motion changes and determine the covering range of depth by motion changes dynamically, the covering range ( $CR$ ) (Figs. 3 and 4) was defined based on the angular velocity equation as

$$CR = k * [(acc * \sin \alpha) + (v * \sin \Delta\theta)], \quad (2)$$

where  $k$  is the adjusting multiplier to balance the covering range and awareness,  $acc$  is the acceleration value,  $\alpha$  is the angle between head direction and linear velocity direction,  $v$  is the linear velocity, and  $\Delta\theta$  is the variation of linear velocity direction during each second. The values of  $acc$ ,  $\alpha$ ,  $v$ , and  $\Delta\theta$  are governed by the camera's motion in Unity (Fig. 3b). To

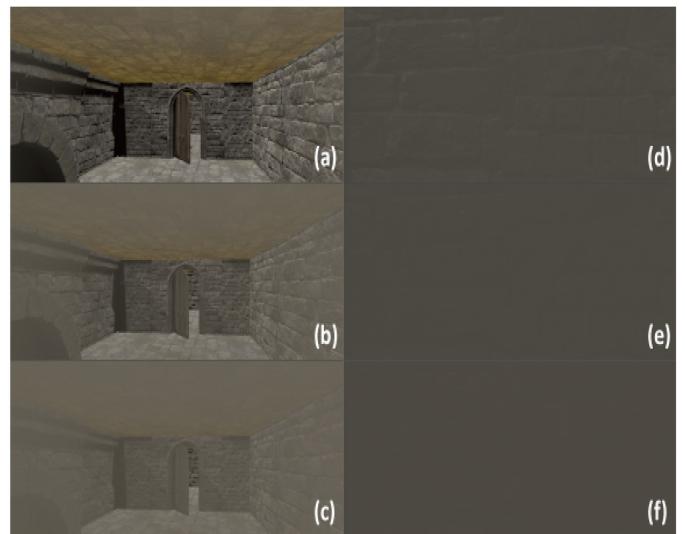


Fig. 4. The effect of the vision modulator during continuous locomotion with different parameters. The left column shows views when facing distant objects, with parameters of (a)  $CR = 10$ , (b)  $CR = 20$ , (c)  $CR = 30$ . The right column shows the effect when a wall is directly in front of the camera, with parameters of (d)  $CR = 10$ , (e)  $CR = 20$ , (f)  $CR = 30$ .

reduce the noticeability of the vision modulator, we squared  $CR$  to make the intensity increase nonlinearly.

We conducted a pilot experiment before the primary experiment to determine an appropriate value for  $k$ . A long indoor hallway VE was built with the same environmental assets and motion triggering objects (cylinders, half-opened doors, stairs, and corners) with which we were going to build the VEs for the primary experiment. Six healthy participants (6 males, mean age 26.67, SD 3.50, all familiar with VR) were recruited for the pilot experiment. They were asked to go through the hallway with a specific  $k$  value and rate the level of disturbance in their vision from the lowest 1 to the highest 7 in each trial. Participants were informed that they were allowed to terminate the experiment at any time point if they felt uncomfortable. To confirm a suitable value of  $k$  and minimize the effect of random fluctuation on subjective rating,  $k$  was first initialized to 0 with a step increase of 1. If a  $k$  value gets a score that is two scores higher than the score when  $k = 0$ , we then initialize  $k$  to a relatively high value (12) with a step decrease of 1. When running this pilot experiment, the disturbance rating typically started to increase at  $k = 1$  and decrease at  $k = 7$ ; therefore, we defined the suitable  $k$  value to be the average,  $k = 4$ .

## 4 EXPERIMENT 1 (CONSECUTIVE TRIALS)

In Experiment 1, we tested three conditions including a control condition, a dynamic FoV restrictor, and the dynamic low-contrast vision modulator in an outdoor VE and an indoor VE with a novel experiment design (see Sections 4.2 and 4.6). Participants experienced each VE while standing in place; however, they were allowed to rotate their head or body to change their heading direction in the VE. In addition, the direction of motion achieved using the joysticks was set relative to the heading direction. We measured the level of VR sickness, the notification level of the modulators, the time participants could have experienced VR sickness, and the position where participants terminated each trial.

We then evaluated the vision modulator against a dynamic FoV restrictor and a control condition with no modulation in these highly interactive VEs to investigate four hypotheses:

- Hypothesis 1: The motion-based vision modulator has a significant effect on mitigating VR sickness induced by controller-based continuous locomotion.
- Hypothesis 2: The motion-based vision modulator is more effective than the other conditions at balancing the trade off between noticeability and VR sickness.
- Hypothesis 3: VEs that have a higher average scene depth of pixels in the participant's view (i.e., the outdoor scene with its skybox) will cause less VR sickness than those that have a lower average scene depth of pixels (i.e., indoor scenes with ceilings).
- Hypothesis 4: The proposed VR-sickness-inducing motions (acceleration, strafing, and linear speed) are potentially more effective at provoking VR sickness than constant forward motions.

### 4.1 Equipment

We used an HTC VIVE Pro Eye HMD with integrated binocular eye tracker, a PC with Intel Core i7-9750H processor (16GB RAM) and NVIDIA GeForce RTX 2070 graphics card.

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The VEs for the experiments were developed in and driven by Unity 2019.3.13f1 and SteamVR. The position and orientation of the cameras in the VEs were governed by the 6DoF pose of the HMD tracked using SteamVR base stations. We used HTC Vive controllers, with the trackpad on the left-hand controller set to control motion as a joystick.

### 4.2 Experiment Design

We conducted the experiment with two separate user groups, one with the outdoor VE and one with the indoor VE. This design allowed us to perform a within-subjects analysis for each of the three sickness alleviation methods, and a between-subjects analysis of the indoor versus outdoor conditions. In each group, all participants experienced all three rendering conditions: a control condition without any visual modification, a condition with a black FoV restrictor, and a condition with our vision modulator.

In both VEs, moving speed was set to a maximum of 2.5m/s, the approximate average running speed of a healthy 20 to 40 year-old human [18]. Participants were randomly assigned to the indoor-VE or outdoor-VE group. For each trial, participants traversed the VE of their group as described in Section 4.3. Participants were asked to end the trial as soon as they started to feel uncomfortable and the time they spent in the VE up to that point was recorded. After each trial, we calculated the "active time" of each participant as

$$AT = RT - IT, \quad (3)$$

where  $AT$  is the active time that a participant is moving with the controller and might be experiencing motion-induced VR sickness in the VE,  $RT$  is the duration from start to finish, and  $IT$  is the time during which the participant was not manipulating the controller. We set the maximum time for each trial to 10 minutes, which we believed to be long enough to induce VR sickness, but short enough that no one would complete the maze task. We recorded velocity, head rotation, and acceleration of each participant to help us understand how their movements were correlated with their reported VR sickness.

For the black FoV restrictor, we reimplemented the algorithm proposed by Fernandes and Feiner [25] and verified that the angular size of the FoV restrictor was correct by using the FoV testing setup shown in Fig. 5. The minimum FoV size was set to  $80^\circ$ , which was demonstrated to be an appropriate value to mitigate VR sickness and reduce awareness in their study. Meanwhile, for the vision modulator condition, we used the proposed algorithm and parameters we defined in Section 3.2.

To ensure that participants experienced motions that could increase VR sickness in the VEs, we used cylindrical obstacle objects to trigger linear rotation, half-opened doors to trigger zig-zag motions, and stair objects to trigger pitch, strafing, and acceleration. Participants would also experience acceleration, rotation, and strafing from their own active motion in the VEs.

### 4.3 Virtual Environment

The experiment was implemented with two VEs, one outdoor and one indoor (Fig. 6), for variety. We first built a maze scene using parts of a castle asset bundle from the

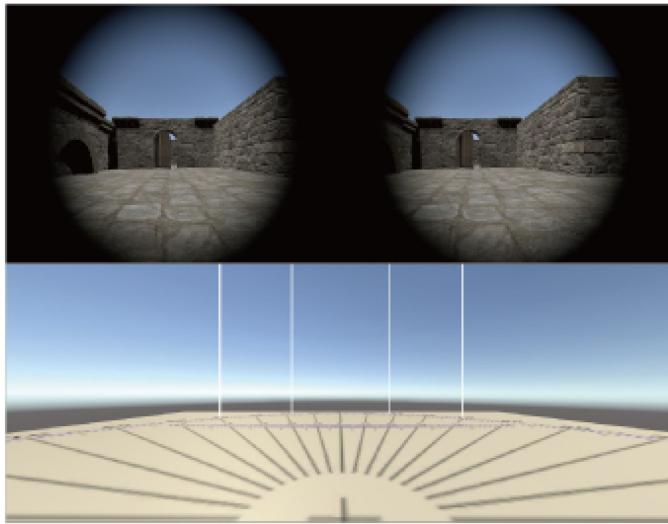


Fig. 5. Implementation of the black FoV restrictor and the degree tester.



Fig. 6. Images showing the outdoor (left) and indoor (right) VEs.

Unity Asset Store [57]. We then added a diverse set of features that would require a variety of different motions and interactions to navigate [37]. The maze (Fig. 7) included five cylindrical obstacles (Fig. 8c), four pairs of stairs (up and down) (Fig. 8b) and 11 half-opened doors (Fig. 8a). Participants were assigned the task of collecting seven keys (Fig. 8d) to unlock the exit. The maze was large enough to support roaming for ten minutes, even when taking the shortest route to collect all the keys and get to the exit.

We aimed to measure the total time participants were moving in the VE regardless of whether they reached the exit, so we did not build different mazes. We modified the

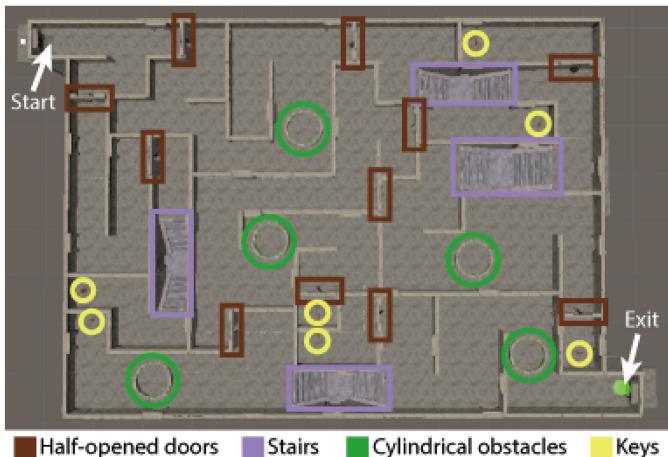


Fig. 7. The map of the maze marked with the locations of the objects. Brown rectangles are doors, purple rectangles are stairs, green circles are wells, and yellow circles are keys.

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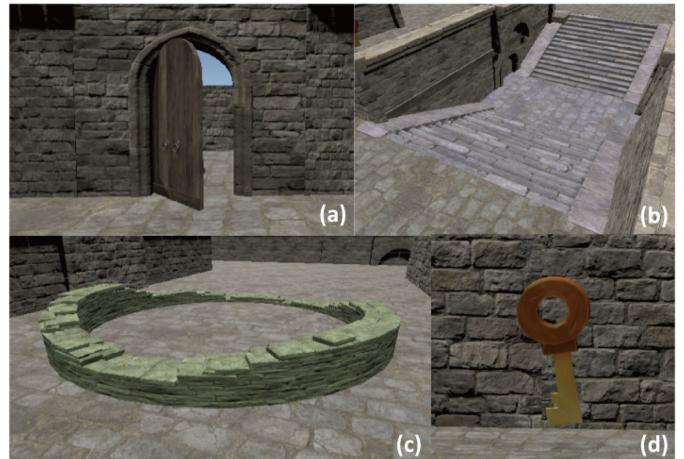


Fig. 8. Some of the objects in the VEs designed to increase controller motions: (a) a half-opened door, (b) stairs, (c) a cylindrical obstacle, and (d) one of the keys needed to open the exit.

maze scene to produce the two VEs used in the experiment. For the outdoor VE, the height of the walls was set to 3m (standard room height) to prevent participants from seeing the route over the walls and at the same time not block the view of the sky (for which we used the default Unity skybox). For the indoor VE, we used the same height for the walls, and added a roof with the same texture as the ground. Thus, participants were not able to see the sky in this indoor maze. All other features (objects, textures, terrains, routes, etc.) were identical across the two VEs. To critically test the noticeability of the vision modulator, we set all of the objects in the VEs to have different colors, as can be seen in Figs. 6 and 8.

#### 4.4 Participants

We recruited 34 people (19 female, mean age 24.03, SD 2.67) to take part in the experiment. All participants had normal vision, little to no experience with VR or video games and similar health conditions. They were informed that they might experience some VR sickness during the experiment and they were allowed to quit the experiment at any time. Furthermore, they were asked if they had any medical history involving their cranial nerve or vestibular system. The experiment was conducted with the approval of an institutional review board (IRB).

The participants were randomly divided into two groups of 17 participants to be tested in the indoor and outdoor experiments, and the three conditions were ordered with a Latin square design.

#### 4.5 Measurements

We gathered data and information from the participants using the Simulator Sickness Questionnaire (SSQ), a post-trial questionnaire, and active time and motion data.

The SSQ [32] is a comprehensive questionnaire for perceived sickness and has been widely applied in studies addressing motion sickness, visually induced sickness, simulator sickness and VR sickness. The SSQ produces a total severity score based on the categories of nausea, disorientation, and oculomotor symptoms. The more VR sickness symptoms are

perceived, the higher the SSQ score will be. We administered the SSQ before and after each trial to determine a participant's sickness status at each time point. To prevent the situation of "getting a higher SSQ score by a longer exposure time" and compare the results from different trials with the same standard, we use the SSQ score difference value divided by active time to calculate the *sickness per minute*, which describes the average increase in sickness score over the exposure time and take that as our main measurement of increased VR sickness of the participant for each trial.

To evaluate the noticeability of each method, we designed a post-trial questionnaire based on a widely used approach in VR studies [25], [46], [59]. Participants were asked to rate the following subjective preference questions on a seven-point scale, from 1 ("Strongly disagree") to 7 ("Strongly agree"):

- I saw the virtual environment flicker.
- I saw the virtual environment get brighter or dimmer.
- *I felt immersed in the virtual environment.*
- I saw that something in the virtual environment had changed shape.
- I felt like I was getting bigger or smaller.
- *I was distracted during the test.*
- I felt like the virtual environment got smaller or larger.

The primary outcome measures (italicized here, but not in the actual questionnaire) were surrounded by distractor questions to avoid biasing participant answers. Furthermore, the questionnaire was presented to participants with a note stating that "These phenomena may or may not have happened."

As described in Section 4.2, we calculated the "active time" (AT) during which participants were exposed to stimuli that would potentially elicit VR sickness. In previous studies, measuring VR sickness in VEs usually relied on self reporting, and participants often terminated the experiment when they were no longer comfortable. This caused some participants to quit the experiment only after suffering strong VR sickness symptoms, extending the time that they participated. In contrast, we asked that participants end each trial as soon as they started to feel uncomfortable, in order to stop just around their subjective threshold [31], [55] and prevent further aggravating symptoms. With this method, we were able to investigate whether the proposed vision modulator could extend the time spent in VR.

## 4.6 Procedure

Before starting the experiment, we briefly introduced the procedures and informed participants about the tasks and requirements. We emphasized that "If you start to feel any sickness, nausea or dizziness, even a little bit, please use the designated controller button to end the trial immediately." Before each trial, the participant completed a pre-exposure SSQ, and then the experimental VE was presented with an HMD. The participant tried to find the exit of the maze until they ended the trial or 10 minutes had elapsed, whichever occurred first. The participant was then asked to complete a post-exposure SSQ and a post-trial questionnaire. After a 10-minute rest, the participant started the next trial, first completing a pre-exposure SSQ. This was repeated until all three conditions were tested.

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Considering that sickness symptoms may remain for a long period [23], [56] or even start to increase approximately 10 minutes after exposure [41], a 10-minute rest time was selected. Thus for the pre-exposure SSQ, similar to the approach used by Nie *et al.* [42], if the participant's pre-exposure SSQ score was higher than 10, he/she was asked to rest for 10 minutes and fill in another pre-exposure SSQ. If this occurred three times (for a maximum rest time of 30 minutes in total before each trial) and the SSQ score was still higher than 10, the participant was asked to come back at a later date. In the actual tests, all participants were able to finish the experiment without having to return on a different day. Since the participants only experienced "just noticeable sickness" instead of long lasting exposure in each trial, this process, together with the Latin square design, would likely alleviate the influence of the residual VR sickness from other trials despite not having a long washout period.

## 4.7 Results

Here, we describe the results of Experiment 1 with respect to the two methods for mitigating VR sickness (FoV restriction and vision modulation), differences between the outdoor and indoor tests, and the effects of motion on the amount of sickness experienced. We used a level of 0.05 for determining significance.

### 4.7.1 Relative Effectiveness of the Modulator and Restrictor

First, we conducted a Shapiro test and created QQ plots, after which we determined that the sickness per minute and SSQ data were not normally distributed. Therefore, we conducted non-parametric tests on these two kinds of data instead of ANOVA/MANOVA.

A Friedman test was first conducted on the amount of sickness per minute for the three conditions: the control condition, black FoV restrictor, and our vision modulator ( $\chi^2 = 16.53, p < 0.001, W = 0.78$ ). Next, Wilcoxon paired tests revealed that both the vision modulator ( $V = 440, p < 0.05, W = 0.85$ ) and the black FoV restrictor ( $V = 453, p < 0.01, W = 0.85$ ) outperformed the control condition (Fig. 9); however, there was no significant difference between the vision modulator and the black FoV restrictor. We separately analyzed the three sub-scale scores and the total severity of the post-SSQ with Friedman and Wilcoxon tests: For nausea ( $\chi^2 = 11.35, p < 0.01, W = 0.90$ ) (Fig. 13a), significance differences were found in the control condition versus the black FoV

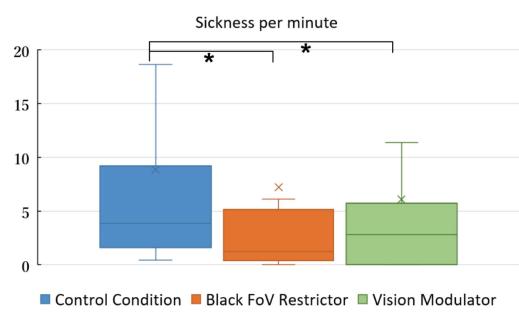


Fig. 9. Subjective sickness results divided by the time in minutes spent in the VE for each condition.

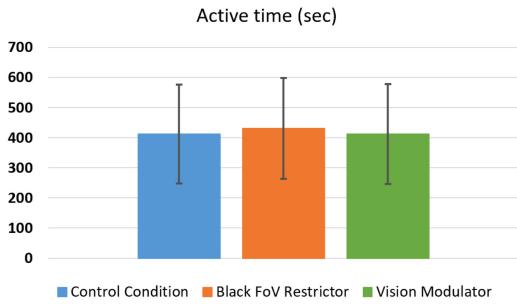


Fig. 10. Active time that participants spent in the VE for each condition.

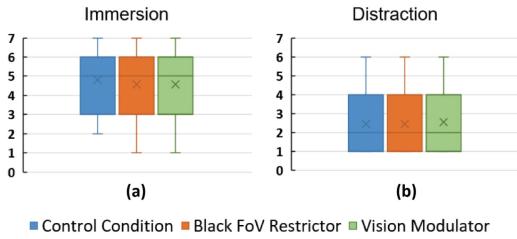


Fig. 11. Rating results of “immersion” and “distraction” from post-trial questionnaires.

restrictor ( $V = 261, p < 0.01, W = 0.82$ ) and the control condition versus the vision modulator ( $V = 272, p < 0.01, W = 0.83$ ). For oculomotor ( $\chi^2 = 7.61, p < 0.05, W = 0.62$ ) (Fig. 13b), a significant difference was found in the control condition versus the vision modulator ( $V = 257, p < 0.05, W = 0.71$ ). For disorientation (Fig. 13c), no significant difference was found ( $\chi^2 = 5.37, p = 0.07, W = 0.84$ ). For total severity ( $\chi^2 = 10.97, p < 0.01, W = 0.74$ ) (Fig. 13d), significant differences were found in the control condition versus the black FoV restrictor ( $V = 297, p < 0.05, W = 0.83$ ) and the control condition versus the vision modulator ( $V = 386, p < 0.01, W = 0.81$ ). A MANOVA test on the active time data found no significant differences between the effectiveness of the three conditions ( $F(2,32) = 3.09, p = 0.87, d = 0.43$ ) (Fig. 10).

Furthermore, we analyzed the data from post-trial questionnaires with Friedman tests, and found no significant differences between the three conditions for the “immersion” ( $\chi^2 = 1.40, p = 0.496, W = 0.77$ ) and “distraction” ( $\chi^2 = 0.03, p = 0.98, W = 0.84$ ) questions (Fig. 11).

#### 4.7.2 Outdoor versus Indoor

To determine whether the outdoor and indoor environments were different when holding all else constant, we

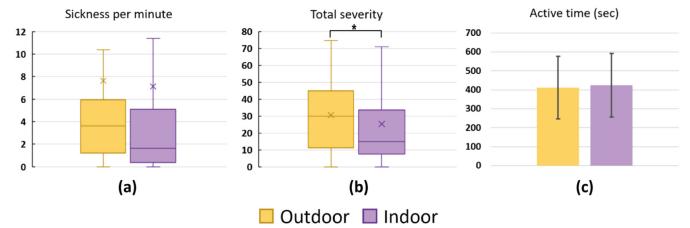


Fig. 12. Data plots of (a) sickness per minute, (b) Total severity and (c) active time for outdoor versus indoor.

analyzed the data of sickness per minute (Wilcoxon,  $V = 478, p = 0.18, W = 0.44$ ), total severity of post-SSQ (Wilcoxon,  $V = 320, p < 0.05, W = 0.48$ ) and active time (MANOVA,  $F(1,50) = 3.94, p = 0.72, d = 0.70$ ). These results revealed that there might be some significant effects of the three conditions in different environments (Fig. 12). Therefore, we proceeded to analyze the total severity data from the three conditions separately with Wilcoxon paired tests, and no further significance was found.

#### 4.7.3 Effects of Motion

The motion data we collected during the experiment included: linear velocity, acceleration, and the angle between head and velocity directions, which were the most likely to have an effect on VR sickness. We used Pearson Correlation between the motion data and sickness metrics separately for each of the three conditions. In addition, outliers beyond three times standard deviation (the “three-sigma rule”) were removed. Regarding average angle differences: For the black FoV restrictor, there was a positive correlation ( $t = 3.24, r = 0.51, p < 0.01$ ) (Fig. 14b). For the control condition ( $t = 1.83, r = 0.31, p = 0.08$ ) (Fig. 14a) and the vision modulator ( $t = 1.87, r = 0.32, p = 0.07$ ) (Fig. 14c), there were no significant correlations. Regarding average linear velocity: For the control condition, there was no significant correlation ( $t = 0.17, r = 0.03, p = 0.86$ ) (Fig. 15a). For the black FoV restrictor, there was a negative correlation

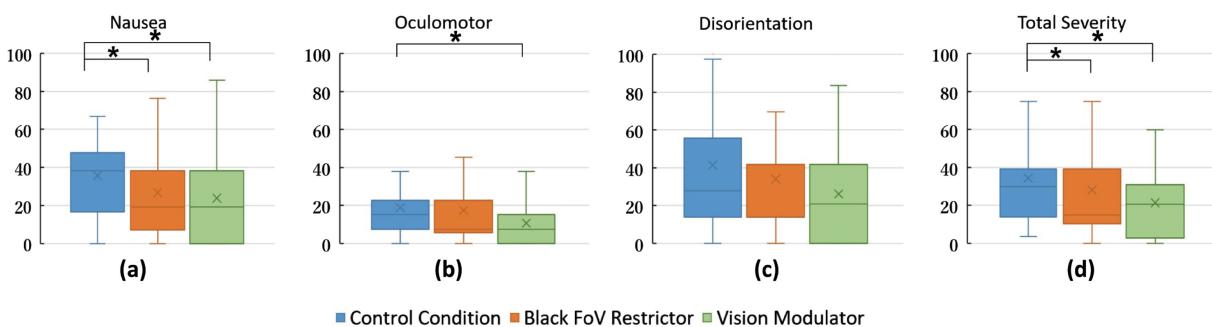


Fig. 13. Analysis of post-SSQ scoring for (a) nausea, (b) oculomotor, (c) disorientation, and (d) total severity, using the formula from Kennedy *et al.* [32].

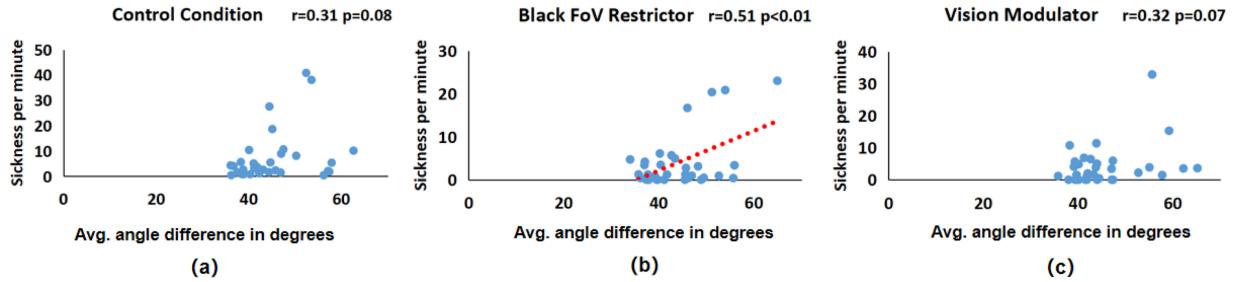


Fig. 14. The Pearson correlation between sickness per minute and average angular difference in degrees between head angle and direction of motion: (b) For the black FoV restrictor,  $r = 0.51$ . For the control condition (a) and the vision modulator (c), no significant correlation were found.

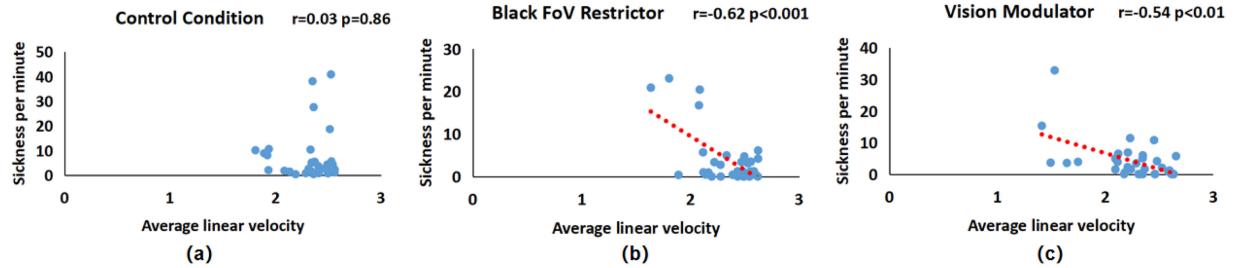


Fig. 15. The Pearson correlation between sickness per minute and average linear velocity: (a) For the control condition, no significant correlation was found. (b) For the black FoV restrictor,  $r = -0.62$ . (c) For the vision modulator,  $r = -0.54$ .

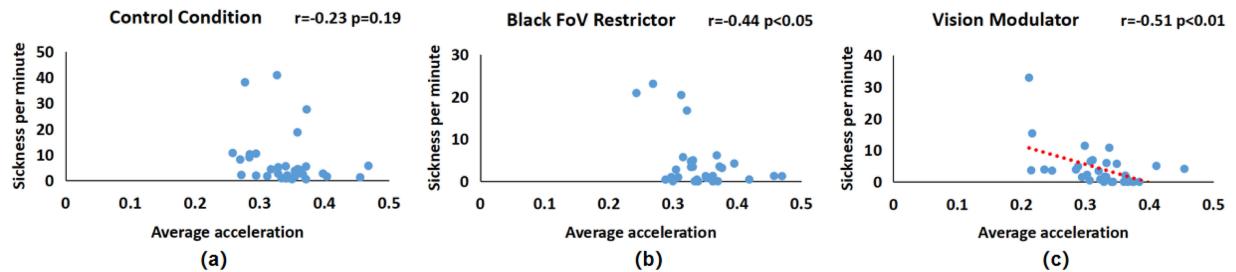


Fig. 16. The Pearson correlation between sickness per minute and average acceleration: For the control condition (a) and the black FoV restrictor (b), no significant correlation was found. (c) For the vision modulator,  $r = -0.51$ .

$(t = -4.37, r = -0.62, p < 0.001)$  (Fig. 15b). For the vision modulator, there was a negative correlation ( $t = -3.56, r = -0.54, p < 0.01$ ) (Fig. 15c). Regarding average acceleration: For the control condition ( $t = -1.35, r = -0.23, p = 0.19$ ) (Fig. 16a) and the black FoV restrictor ( $t = -2.69, r = -0.44, p < 0.05$ ) (Fig. 16b), there were no significant correlation. For the vision modulator, there was a negative correlation ( $t = -3.27, r = -0.51, p < 0.01$ ) (Fig. 16c).

## 5 EXPERIMENT 2 (MULTI-DAY TRIALS)

In Experiment 2, we tested the three conditions in the two VEs with a longer washout time; everything else remained the same as in Experiment 1 (Section 4).

### 5.1 Participants

We recruited 22 people (11 female, mean age 24.05, SD 2.17) to take part in the experiment. All participants had normal vision, little to no experience with VR or video games and similar health conditions. They were informed that they might experience some VR sickness during the experiment and they were allowed to quit the experiment at any time. Furthermore, they were asked if they had any medical history involving their cranial nerve or vestibular system. The

experiment was conducted with the approval of an institutional review board (IRB).

The participants were randomly divided into two groups of 11 participants to be tested in the indoor and outdoor experiments, and the three conditions were ordered with a Latin square design.

### 5.2 Procedure

Before starting the experiment, we briefly introduced the procedures and informed participants about the tasks and requirements. We emphasized that "If you start to feel any sickness, nausea or dizziness, even a little bit, please use the designated controller button to end the trial immediately." Before each trial, the participant completed a pre-exposure SSQ, and then the experimental VE was presented with an HMD. The participant tried to find the maze exit until they ended the trial or 10 minutes had elapsed, whichever occurred first. The participant was then asked to complete a post-exposure SSQ and a post-trial questionnaire. The three trials were conducted on separate days [1], [25].

For the pre-exposure SSQ, similar to the approach used by Nie *et al.* [42], if the participant's pre-exposure SSQ score was higher than 10, he/she was asked to rest for 10 minutes and fill in another pre-exposure SSQ. If this occurred three

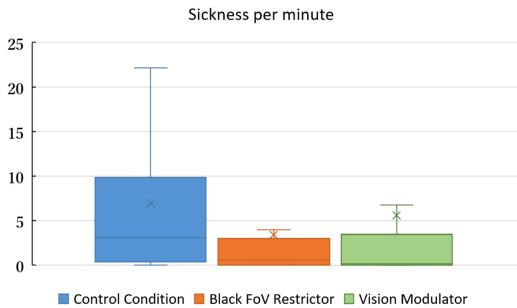


Fig. 17. Subjective sickness results divided by the time in minutes spent in the VE for each condition.

times (for a maximum rest time of 30 minutes in total before each trial) and the SSQ score was still higher than 10, the participant was asked to come back at a later date. In the actual tests, all participants were able to finish each trial without having to return on a different day.

### 5.3 Results

In this section, we describe the results of Experiment 2 with respect to the two methods for mitigating VR sickness (FoV restriction and vision modulation), differences between the outdoor and indoor tests, and the effects of motions on the amount of sickness experienced. We used a level of 0.05 for determining significance.

#### 5.3.1 Relative Effectiveness of the Modulator and Restrictor

Using the same statistical analysis as Experiment 1, we conducted a Shapiro test and drew a QQ plot, which helped us determine that the sickness per minute data and SSQ were not normally distributed. After that, we conducted non-parametric tests on the two kinds of data instead of ANOVA/MANOVA.

A Friedman test was first conducted on the amount of sickness per minute for the three conditions: the control condition, black FoV restrictor, and our vision modulator. No significant difference ( $\chi^2 = 3.34, p = 0.19, W = 0.55$ ) between the three conditions was found (Fig. 17). We separately analyzed the three sub-scale scores and total severity of the post-SSQ with Friedman and Wilcoxon tests: For oculomotor ( $\chi^2 = 7.42, p < 0.05, W = 0.57$ ) (Fig. 21b), significant differences were found in the control condition versus the black FoV restrictor ( $V = 102, p < 0.05, W = 0.62$ ) and the control condition versus the vision modulator ( $V = 114, p < 0.05, W = 0.60$ ). Moreover, no significance was found for nausea ( $\chi^2 = 2.03, p = 0.36, W = 0.66$ ) (Fig. 21a), disorientation ( $\chi^2 = 2.94, p = 0.23, W = 0.60$ ) (Fig. 21c) or total severity ( $\chi^2 = 4.46, p = 0.11, W = 0.61$ ) (Fig. 21d). We also applied a MANOVA test on the active time data and found no significant differences between the effectiveness of the three conditions ( $F(2,20) = 3.15, p = 0.24, d = 0.55$ ) (Fig. 18).

Furthermore, we analyzed the data from post-trial questionnaires with a Friedman test, and found no significant difference between the three conditions for the “immersion” ( $\chi^2 = 0.72, p = 0.70, W = 0.22$ ) and “distraction” ( $\chi^2 = 1.10, p = 0.58, W = 0.29$ ) questions (Fig. 19).

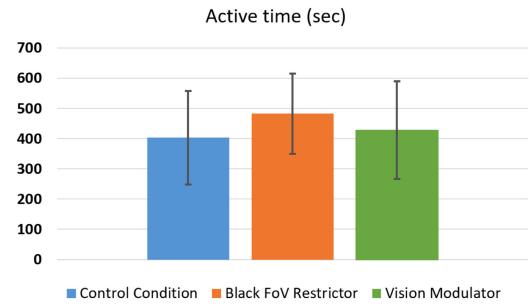


Fig. 18. Active time that participants spent in the VE for each condition.

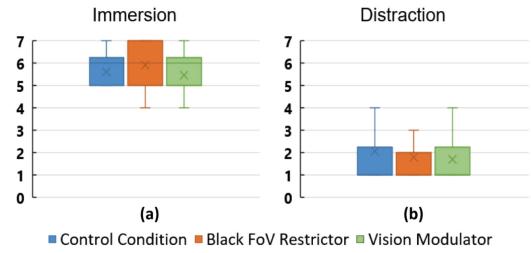


Fig. 19. Rating results of “immersion” and “distraction” from post-trial questionnaires.

#### 5.3.2 Outdoor versus Indoor

To determine whether the outdoor and indoor environments were different when holding all else constant, we analyzed sickness per minute (Wilcoxon,  $V = 192, p = 0.95, W = 0.63$ ), total severity of post-SSQ (Wilcoxon,  $V = 162, p = 0.75, W = 0.71$ ), and active time (MANOVA,  $F(1,32) = 3.15, p = 0.24, d = 0.79$ ). These results revealed that there was no significant effect of the three conditions in different environments (Fig. 20).

#### 5.3.3 Effects of Motion

The motion data we collected during the experiment included: linear velocity, acceleration, and the angle between head and velocity directions, which were the most likely to have an effect on VR sickness.

The motion data were collected and compared with sickness per minute similar to Experiment 1 (Section 4.7.3). Regarding average angle differences: For the black FoV restrictor, there was a positive correlation ( $t = 2.51, r = 0.50, p < 0.05$ ) (Fig. 22b). For the control condition ( $t = -1.32, r = -0.29, p = 0.20$ ) (Fig. 22a) and the vision modulator ( $t = 1.50, r = 0.33, p = 0.15$ ) (Fig. 22c), there was no significant correlation. Regarding average linear velocity: For the control condition, there was a negative correlation ( $t = -3.80, r = -0.66, p < 0.01$ ) (Fig. 23a). For the black FoV restrictor, there was a

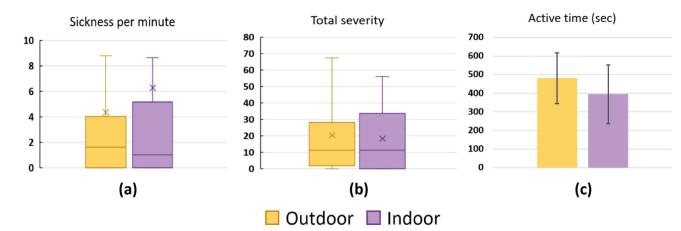


Fig. 20. Data plots of (a) sickness per minute, (b) Total severity and (c) active time for outdoor versus indoor.

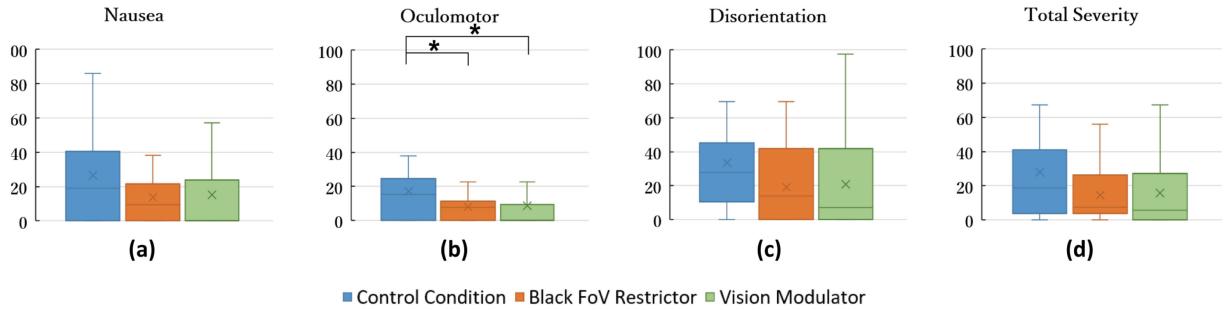


Fig. 21. Analysis of post-SSQ scoring for (a) nausea, (b) oculomotor, (c) disorientation, and (d) total severity, using the formula from Kennedy *et al.* [32].

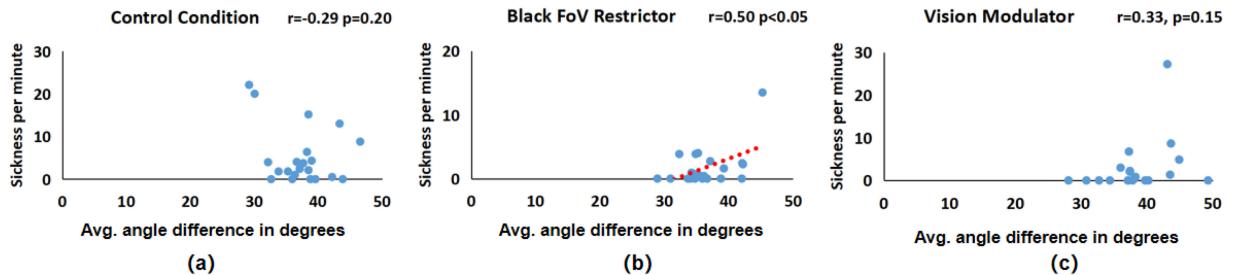


Fig. 22. The Pearson correlation between sickness per minute and average angular difference in degrees between head angle and direction of motion: (b) For the black FoV restrictor,  $r = 0.50$ . For the control condition (a) and the vision modulator (c), no significant correlation were found.

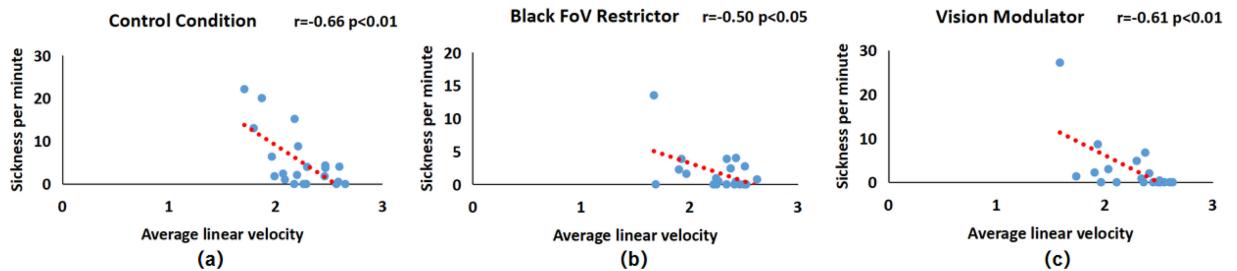


Fig. 23. The Pearson correlation between sickness per minute and average linear velocity: (a) For the control condition,  $r = -0.66$ . (b) For the black FoV restrictor,  $r = -0.50$ . (c) For the vision modulator,  $r = -0.61$ .

negative correlation ( $t = -2.52, r = -0.50, p < 0.05$ ) (Fig. 23b). For the vision modulator, there was a negative correlation ( $t = -3.27, r = -0.61, p < 0.01$ ) (Fig. 23c). Regarding average acceleration: For the control condition, there was a negative correlation ( $t = -3.38, r = -0.61, p < 0.01$ ) (Fig. 24a). For the black FoV restrictor ( $t = -1.46, r = -0.32, p = 0.16$ ) (Fig. 24b) and the vision modulator ( $t = -1.62, r = -0.36, p = 0.12$ ) (Fig. 24c), there were no significant correlation.

## 6 DISCUSSION

The results we gained from Experiment 1 demonstrated some effectiveness of the proposed vision modulator. In addition, our findings also indicated that the low-contrast effect is helpful in reducing VR sickness. The experimental results suggested that the visual methods were neither distracting nor noticeable, so they would not likely affect the conscious perception ofvection [51]. Our goal is to preserve

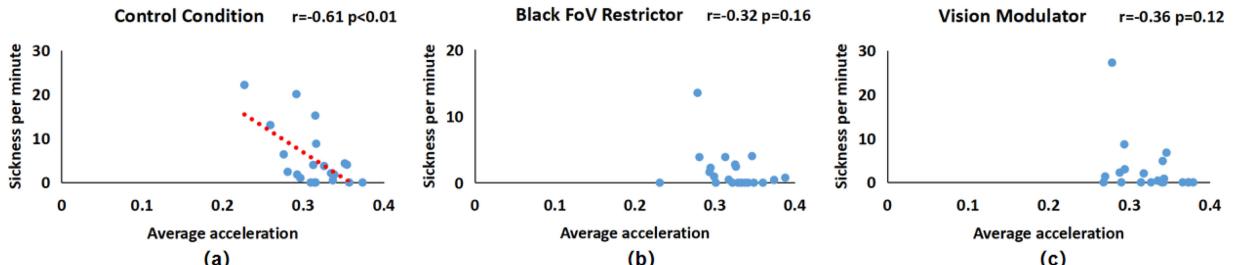


Fig. 24. The Pearson correlation between sickness per minute and average acceleration: (a) For the control condition,  $r = -0.61$ . For the black FoV restrictor (b) and the vision modulator (c), no significant correlation were found.

the conscious perception of self motion, but reduce intersensory conflict (i.e.,vection in the periphery that is not consciously perceived but contributes to VR sickness), while preservingvection in the central field of view.

## 6.1 Experiment Results (Consecutive Trials)

Based on the sickness per minute data and the total severity data, both the black FoV restrictor and the vision modulator outperformed the control condition, which supports our H1. Although the two methods did not show an overall significant difference, there was a difference. The SSQ oculomotor score indicated that participants experienced significantly less severe oculomotor symptoms with the vision modulator. On the other hand, the black FoV restrictor did not have an effect on the measure.

Unlike FoV restrictors, our vision modulator is not restricted to a 2-D FoV radius, and it can modify pixels both in central vision and the periphery. It also dynamically changes size, depth and intensity based on motion. Therefore, with unblocked peripheral vision, users should not need to turn their eyes and heads as often as with a restricted FoV while moving in a complex VE. After the experiment, several participants orally reported that they thought the black FoV restrictor was effective when they were moving straight ahead and the vision modulator was effective when they were trying to cross the half-opened doors or moving on the stairs. These observations supported the results obtained from the oculomotor and disorientation scores.

Regarding H2, our analysis of the post-trial questionnaires revealed that participants did not feel any significant loss of immersion or strong distraction with both of the VR sickness mitigating methods, which is in line with the demonstration that Zielasko *et al.* [66] have made on the distraction of dynamic peripheral rendering. However, this does not mean that the methods were unnoticeable all the time. During the experiment, several participants orally reported that they noticed a “black shadow” in front of their eyes or they felt like there was something getting darker when they were tested with the black FoV restrictor. On the other hand, several participants orally reported that they noticed “fog” in their view or that they felt like the lenses were unclear when they were tested with the vision modulator. However, these experiences may also be induced by our VEs, since a few participants orally reported perceiving uncleanness and shadows in the control condition. We believe that as long as the method is designed to counterbalance visual sensory conflicts, users are likely to notice it at some point in time. Instead of pursuing “unnoticeable” approaches, future studies might focus on making the method less distracting or more immersive by designing it to be more consistent with the VEs or the users’ operations.

In H3, we proposed that outdoor VEs may induce less VR sickness than indoor VEs since there are fewer low-depth pixels toward the front of the participant’s view. Especially when the skybox is completely blue, pixel movements would not be noticed. Therefore the overall percentage of high visual angular velocity area in outdoor VEs would be lower and produce lower “sensory rearrangement” [44] than the indoor VEs. However, our experimental results did not support this hypothesis. Considering that participants moved freely and looked freely in the

experiment, they did not keep the sky in their view all the time when they were traveling through the outdoor VE. On the other hand, since our maze was relatively large, there were also high-depth areas in view of the participants in the indoor VE. In addition, we designed the VEs to be highly interactive and contain a lot of objects, which also affected the visual angular velocity of a participant’s view.

Regarding H4, during the experiment, many participants reported that their feeling of VR sickness was accelerated by the half-opened doors and the stairs. This indicates that the objects successfully induced VR sickness by forcing the participant to move in a non-linear fashion. These movements were recorded when there was an angle kept between the velocity vector and the head-facing vector and were calculated as average strafing per frame. The Pearson correlation between strafing and VR sickness revealed a positive correlation for the black FoV restrictor. The Pearson correlation between linear velocity and VR sickness revealed negative correlations for both the black FoV restrictor and the proposed vision modulator, which suggests that they effectively mitigated VR sickness induced by increases in linear velocity. The Pearson correlation between acceleration and VR sickness revealed a negative correlation for the proposed vision modulator, which is reasonable since acceleration was taken into consideration in our algorithm. Lastly, for the control condition, no significant correlation between all the motion data and VR sickness was observed, which opposed our H4.

## 6.2 Experiment Results (Multi-Day Trials)

Experiment 2 was conducted to determine if we could support the findings of Experiment 1, as well as to explore the effectiveness of different washout periods, the reliability of a just-noticeable-sickness design, and the adaptability of designs with different rest periods.

The results from Experiment 2 did not show as many significant differences for either the proposed vision modulator or pitch-black FoV restrictor, though our findings did indicate that the two methods were still helpful in reducing oculomotor symptoms. One reason for this may be that since shorter multi-day trials allowed for longer rest periods, participants simply experienced less sickness overall. Still, the severity of the oculomotor-related effects was significantly decreased between control and vision modulator/FoV restrictors, confirming that the vision modulator can reduce symptoms in a similar fashion to FoV restrictors without affecting other perceptions. This is evidenced by the similar results regarding active time, post-trial questionnaires, outdoor versus indoor environments, and the correlation between strafing and VR sickness.

For the control condition, the correlation between linear velocity and VR sickness and the correlation between acceleration and VR sickness was negative. This result demonstrated that as linear velocity and acceleration values increased, users may feel less sick during locomotion. This finding was aligned with the demonstration by Alexander *et al.* [2].

## 6.3 Comparison of Experiments

During Experiment 2, on many occasions participants indicated that differences in physical state (e.g., sleep, hunger,

fatigue) on different days likely affected the sickness they experienced. This is a significant trade-off for experiment designs that implement a washout period of a day or more. In addition, participants reported that their standards for judgement when answering the SSQ questions and defining thresholds of sickness may also have varied on different days. In Experiment 1, the just-noticeable-sickness metric was designed to prevent the occurrence of severe symptoms, as well as the transference of symptoms into future trials, which is another trade-off between participant comfort, consistency of judgement, and residual effects of any remaining sickness. It may be beneficial to explore a single-day design in which participants experience trials several hours apart instead of several days apart to reduce the potential variability introduced by different cognitive or physical states for participants on different days. As such, future experiments on VR sickness should consider the trade-offs of both experimental designs and make a decision based on the specific needs and outcomes of the experimental task. If minimization of sickness symptoms is desired, shorter, multi-day trials may be justified.

Both Experiments 1 and 2 indicated that the black FoV restrictor and the vision modulator did not provoke enough distraction to affect immersion during the exposure time. Meanwhile, both methods did not show any significant help to extend the active time in our experiments, which revealed that although the methods may mitigate (Experiment 1) the feeling of VR sickness, they were not able to lengthen the time users would like to stay in VEs. Therefore, we suggest that future studies on motion-induced VR sickness should consider other motions. Regarding outdoor versus indoor environments, no statistically significant differences between them were found in either experiment, which does not indicate that average scene depth of a pixel should be considered as a factor in inducing VR sickness. Regarding the correlation between strafing and VR sickness for the black FoV restrictor, both of the experiments indicated a positive correlation, which is similar with the findings by Norouzi *et al.* [43]. This result might be caused by the smaller FoV, since participants have to rotate their head with a larger range and more often to counterbalance the restricted FoV. Additionally, ordering effects of session may have existed, but were alleviated by the Latin square design.

## 7 CONCLUSIONS AND FUTURE WORK

In this paper, we performed two cross-group within-subjects experiments to investigate the performance of a novel motion-based dynamic low-contrast shading technique designed to mitigate VR sickness. This method performs real-time sampling of scene pixels to blend scene color into the user's FoV, integrates user motion so that it engages only during movements that cause intersensory conflict, and uses depth-based rendering. In Experiments 1 and 2, 34 and 22 participants, respectively, were randomly divided into two groups and experienced three conditions using a VR display: a control condition with no modification, an experimental condition with a black FoV restrictor, and an experimental condition with the proposed approach.

The data collected from Experiment 1 demonstrated that both the black FoV restrictor and the proposed approach

effectively mitigated visually induced VR sickness and enabled users to remain in VEs for a longer period of time than the baseline without a significant awareness of the modulator. In addition, since the VEs in the experiments were designed with multiple colors in order to test whether our approach could effectively maintain a low sense of distraction, the multiplier  $k$  was set to a relatively low value. It may be the case that this type of shading will be more effective in well-designed commercial VEs with more consistent ambient colors. Our implementation of FoV modifications revealed similar results to Fernandes and Feiner's study, which showed that their intervention helped participants to experience less VR sickness with no significant distraction. In contrast to other short washout period studies [22], [27], we provided an additional long washout period experiment to investigate whether washout periods make a big difference. In future studies, we plan to further explore shading algorithms that can better reproduce scene coloration without generating optical flow. We also plan to conduct experiments testing individual motions such as acceleration and rotation. Moreover, we would like to investigate the effectiveness of the proposed approach with longer exposure times, in other environments such as games, and during more interactive tasks.

We hope that this work will encourage the development of other motion-dependent shading techniques that can reduce VR sickness and maintain a sense of immersion as well as the exploration of short-washout-period, just-noticeable-sickness experimental designs.

## ACKNOWLEDGMENTS

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