

# Reducing Visual Discomfort with HMDs Using Dynamic Depth of Field

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**R**ecent advances in hardware technology have led to the production of consumer appropriate head-mounted displays (HMDs) such as the Oculus Rift, which is theoretically ideal for personal use in immersive virtual reality (VR) applications including gaming, simulation, and film. Support from established companies such as Valve

feedback loop, where their discomfort actually increases over repeated exposure. Thus, it is impractical to rely on such an acclimatization period for reducing discomfort. A solution that addresses discomfort experiences during a user's first HMD exposure is therefore essential to VR's continued growth and adoption.

The human visual system uses a number of cues to infer depth and distance including accommodation (the flexion of the lens in the eye required to form a focused image on the retina) and vergence (the inward rotation of the eyes required to form a single, binocular image). In stereo displays, these cues do not match, because the accommodation required to bring the physical HMD screen into focus will rarely match the vergence required to fuse the stereo image pair into a single binocular image, as Figure 1 shows. This is caused by the requirement that the eyes converge at different depths, depending on the virtual depth of the observed object in the stereoscopic scene. The result of this mismatch is a conflict in the expected depths of visual stimuli, which is known to be a cause of visual discomfort.<sup>4</sup> In stereoscopic 3D viewing, if the accommodative demand is fixed (as is the case for HMDs such as the Oculus) and the vergence demand is changing, a greater rate of change in the vergence demand will result in greater visual discomfort. This indicates that it is not just the existence of a conflict between accommodation and vergence demands that leads to discomfort; the requirement for the visual system to consistently re-adapt to new, conflicting demands is also a factor.

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Although head-mounted displays (HMDs) are ideal devices for personal viewing of immersive stereoscopic content, exposure to VR applications on HMDs can result in adverse physical reactions (eye fatigue, headaches, nausea, and sweating). This study shows that depth-of-field blur can decrease overall visual discomfort with HMDs.

that users commonly report adverse physical reactions—including headaches, nausea, dizziness, and eye strain—when using them. Collectively, these symptoms represent a condition termed *simulator sickness*,<sup>1</sup> which reportedly affects up to 80 percent of HMDs users.<sup>2</sup>

Repeated exposure to VEs on HMDs is known to reduce the severity and incidence of visual discomfort,<sup>3</sup> but some users experience a negative

Following the suggestion that modifications to HMD hardware are required to reduce visual discomfort,<sup>5</sup> new hardware solutions such as the light field HMD have been proposed. According to a recent perceptual study,<sup>6</sup> gaze-contingent depth of field (DoF) can reduce visual discomfort when viewing stereoscopic content on LCD monitors viewed through a haploscope. This study used an external eye-tracking system to accurately calculate participants' gazes when using the haploscope. The requirement for such external hardware is intrusive in user evaluations of consumer-level devices and may not accurately represent viewing conditions for users outside the lab.

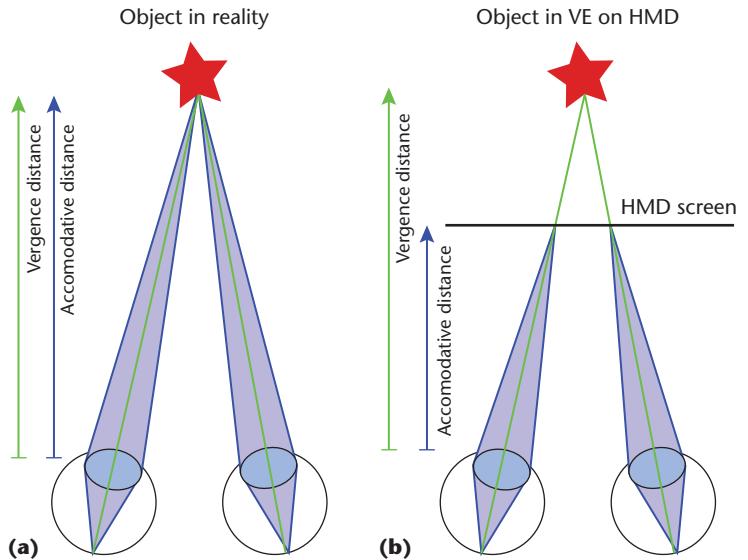
In this article, we perceptually evaluate the human visual system to show the effectiveness of dynamic DoF blur in mitigating visual discomfort when using stereoscopic HMDs. This is the first experimental report to investigate the effectiveness of dynamic DoF blur on HMDs. Our test system can be implemented without any hardware modification, and it does not require the use of intrusive external devices. It relies only on positional data already captured by the Oculus. We implemented a real-time dynamic DoF system in the Unreal Engine (version 4) and performed a series of user tests to show the effectiveness of dynamic DoF blur on the Oculus.

## HMDs and Viewing Comfort

HMDs provide an immersive viewing environment appropriate for VR applications and can be classified according to the configuration of the HMD's screen and optics. According to previous surveys,<sup>7</sup> HMDs fall into three categories: **stereoscopic**, where the illusion of depth is created by delivering images rendered from different angles to each eye; **monoscopic**, where identical content is delivered to each eye; and **bioptic**, where only a single display is present that is viewed by both eyes. **The Oculus is a stereoscopic HMD.**

## Simulator Sickness

In 1958, findings were released on the incidence of symptoms similar to motion sickness in users of the 2-F2-H Hover Trainer, a training simulator for helicopter pilots. These symptoms would later come to be grouped under the name **simulator sickness**, "a term used to describe the diverse signs or symptoms that have been experienced by flight crews during or after a training session in a flight simulator."<sup>1</sup> The label is now used to describe "discomfort [occurring] in a simulator of any kind." Simulator sickness symptoms fall into three groups<sup>8</sup>: oculomotor symptoms such as eye



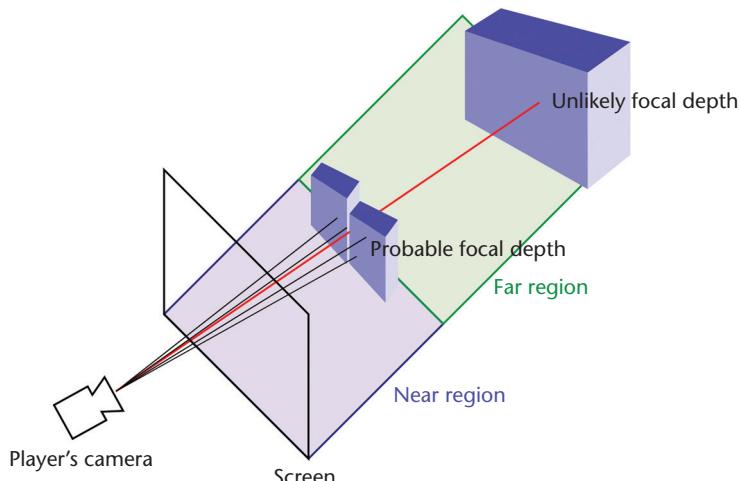
**Figure 1. The accommodation–vergence conflict. Comparing visual situations in (a) real life and (b) when seeing objects in a virtual environment (VE) on a HMD.**

strain, blurry vision, and headaches; disorientation symptoms such as dizziness and vertigo; and nausea symptoms such as changes in salivation and stomach awareness. Some symptoms may contribute toward overall discomfort in more than one group—blurry vision can contribute to both the oculomotor and disorientation discomfort categories, for example. Simulator sickness symptoms also occur during HMD use, indicating such symptoms arise in a far greater variety of immersive VR applications than was initially expected.

The causes of simulator sickness can be categorized into two major groups: inconsistencies between simulator viewing conditions and reality including latency, inconsistent geometric, and display field of view, and accommodation–vergence conflict; and immersion resultant causes includingvection and abnormal motions.

Inconsistencies between simulator viewing conditions and reality can be considered similar to (and identical to, if the display's field of view is incorrect) the readjustment period required to learn a new vestibulo-ocular reflex when people first use a new glasses prescription. That is, the brain "remembers" the expected visual behaviors for certain stimuli, and if the actual stimulus does not match this expectation, it leads to discomfort. Latency is of particular note on HMDs where the head is not fixed, as we expect the display to update at the same rate as our eyes when the head moves, and even small time disparities in an update of the visual field are noticeable and discomforting.

Research has shown that unusual visual orientations are discomforting and that unrestrained



**Figure 2.** Determining scene-space depth. To avoid users focusing at unlikely depths (red), multiple rays (black) are cast to find  $d_f$ .

head movements that allow such viewing conditions especially contribute to sickness.<sup>9</sup> Simulators (especially HMDs) allow for viewing conditions that are not typically possible in reality, and they offer levels of immersion high enough to create a presence illusion, causing visual discomfort. Blur effects such as DoF can also mask the effects of higher latencies, increasing viewer comfort.

### Reducing Visual Discomfort

Viewing monoscopic or stereoscopic content with a small angle of difference between the two images (micro-stereoscopic) results in less discomfort compared with viewing identical stereoscopic content; removing and/or minimizing the vergence cues for depth and distance estimation reduces discomfort. Researchers found that occlusion of peripheral vision on HMDs is a contributor to visual discomfort<sup>5</sup> because not being able to view content external to the HMD screen exacerbates the sensory conflict between the vestibular and ocular systems.

Other attempts to explicitly solve the accommodation-vergence conflict in stereoscopic displays have also used hardware-based approaches involving setups such as multifocal displays, alternative lens systems, or multilens systems. These architectures all provide close-to-correct accommodation cues for multiple depths, but their complex construction prohibits easy application to consumer-level devices such as the Oculus at this time.

### Visual Perception of DoF Blur

Blurring effects are known to serve as a cue for perceiving an object's size, and in conjunction with cues such as binocular disparity (featured in all stereoscopic implementations), they also serve to alter the perception of quantitative depth. Adding

blur gradients to simulate DoF and peripheral blur improves game play quality and realism in a single display, and DoF blur can reduce rivalry from monocular regions in stereoscopic images, indicating that DoF blur should decrease visual discomfort without negatively impacting the VE's quality.

Blur effects are known to alleviate the accommodation-vergence conflict in stereoscopic displays by masking high-frequency spatial data and to ease the fusion of stereoscopic content, increasing viewing comfort.<sup>10</sup> In addition, implementing dynamic DoF lets users perceive images more realistically, with an increased sense of depth.

### Perceptual Study of DoF

Focal cues including artificial blur and accommodation directly contribute to the quality of a 3D experience by reducing visual fatigue. Furthermore, correcting these cues is one of the most important factors for viewing comfort. Correct focusing when viewing content on a stereoscopic display reduces visual fatigue and discomfort by lessening the strain caused by the accommodation-vergence conflict.<sup>11</sup> No prior perceptual studies have been completed to report the impact of using DoF blur to reduce accommodation-vergence conflict in the use of stereoscopic HMDs.

### Experiment Setup

In typical gaming conditions, approximately 86 percent of users' fixation time and 82 percent of their total viewing time is spent looking at the center of the screen.<sup>12</sup> Given that DoF blur effects are also known to drive user focus, we assume that combining screen-center fixation bias and a DoF algorithm that keeps the center of the screen in focus will drive user fixation such that no eye tracking is required to estimate user focus.

We implement real-time dynamic DoF that keeps the center of the screen in focus using a GPU. Our DoF implementation simulates bokeh blur using a circle of confusion (CoC). To begin, we find the scene-space depth of the object at the center of the screen,  $d_f$ . Given that the Oculus has a rather low-resolution screen ( $640 \times 800$  per eye), the angular distance between pixels (as seen by the HMD user) is much larger than plausible angular differences between objects in the VE. As a result, it is difficult to determine whether the object exactly in the center of the screen (in screen space) is the actual object being focused on, especially if foreground images have a small gap between them (see Figure 2).

Hence, to find  $d_f$ , we cast nine rays into the scene—one directly at the center of the screen, and

eight at small regular angular deviations around it. The average of these distances, less outliers, is then taken as  $d_f$ . Using a circular bokeh blur kernel, the blurred scene is generated using Algorithm 1 in Figure 3.

As the user's neck moves, a corresponding movement of the player camera will occur in the VE, changing the depth of the object under the center of the screen. **Immediately changing to a new focal depth would be jarring for users because the human eye takes up to 500 ms to refocus.** The time taken to refocus across a given distance differs depending on the user's age and eye condition as well as the light levels. For real-time performance, we simply assume all users will take a static 500 ms to refocus from an infinite distance to a close distance ( $\approx 1$  m), using the value calculated in earlier work<sup>13</sup> (assuming a typical adult's eyes). **This translates to a linear interpolation between focal distances that takes  $\approx 1.7 \mu\text{s}$  to refocus per meter.**

Blur parameters such as the maximum CoC radius  $r_{\max} = 1.75$  percent of the screen width and the distance at which focus is assumed to be infinite  $d_{\max} = 30$  km were selected using a preliminary experiment where a test environment was generated that consisted multiple identical objects at differing visual depths, as Figure 4 shows. We assume a fixed inter-pupillary distance (IPD) of 63 mm, which is the average gender-independent value for adults.

Participants completed the study on a machine running Windows 7 with 8 Gbytes of RAM, a 3.6 GHz Intel quadcore CPU, and a Nvidia GTX 770 GPU with an attached Oculus Rift DK1 HMD. Figure 5 shows an example of the experimental setup.

## Stimuli

The participants in our study were shown two scenes: a **temple** and a **mountainous landscape** (see Figure 6). These specific scenes were chosen in order to represent broad VR applications. The temple scene consists of primarily near focal distances, with three separate rooms with different illuminations: **bright, natural, and dark**. All three rooms included **highly detailed objects** that a user could pay close attention to at close range. The mountainous landscape in contrast, consists of primarily far focal distances with a **few highly detailed objects**.

**A total of 20 participants took part, with an age range of 18 to 50 years old.** Six participants were female, and the rest were male. The study had 34 volunteers, but we excluded 14 because they either had prior experience with HMDs and/or self-reported abnormalities or aberrations of their

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for Each pixel  $p_i$  in the unblurred scene
    Calculate  $d_i$ , the depth of the object under  $p_i$ 
    Calculate the radius  $r_i$  for the corresponding circle of confusion (CoC)
     $r_i \propto |d_f - d_i| * r_{\max}$ 
    Scale the circular blur kernel  $M_i$  by  $r_i$ 
end for
Create an output image  $Q$  consisting of pixels  $q_{0..n}$ 
for Each pixel  $p_i$ 
    Calculate  $N_i$  by multiplying  $p_i$  (RGB channel) by  $M_i$ 
    Blend  $N_i$  into  $Q$ , centered at  $q_i$ 
end for
Return  $Q$ 

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Figure 3. Algorithm 1. The blurred scene is generated using a circular bokeh blur kernel.

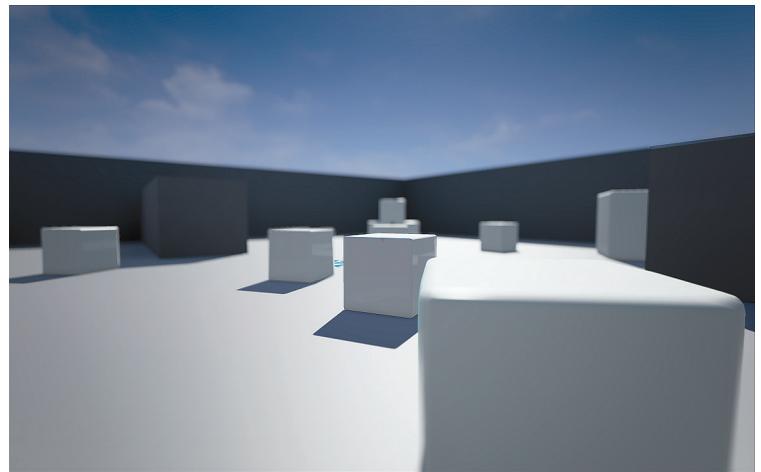


Figure 4. The test scene used for selecting depth of field (DoF) blur radius. With this test environment, we selected the blur parameters and focus distance.



Figure 5. Example experimental setup. A participant wearing the Oculus Rift during the user study.



**Figure 6.** Sample screenshots of the test scenes. (a) The temple and (b) mountainous landscape were displayed with DoF enabled (left) and disabled (right).

visual systems. The participants were recruited using posters placed around our university campus and via relevant local forums.

Using a control scheme proposed by Valve Software, the participants interacted with the two scenes. The Oculus's view vector is independent of the motion vector of the user's virtual avatar. The user controls their avatar's movement using the keyboard to move forward or backward or to strafe left and right; they use the mouse to rotate their avatar's torso; and they control the camera's roll, pitch, and yaw using the orientation of the Oculus (controlled by moving the neck). We disabled jumping in our study, and the user was limited to a velocity of  $1.4 \text{ ms}^{-1}$  to minimize discomfort arising from factors related to traversing the VE. Similarly, if a user's velocity had a nonzero vertical component (such as when they walked up stairs), their horizontal velocity was decreased to compensate, keeping their total velocity constant.

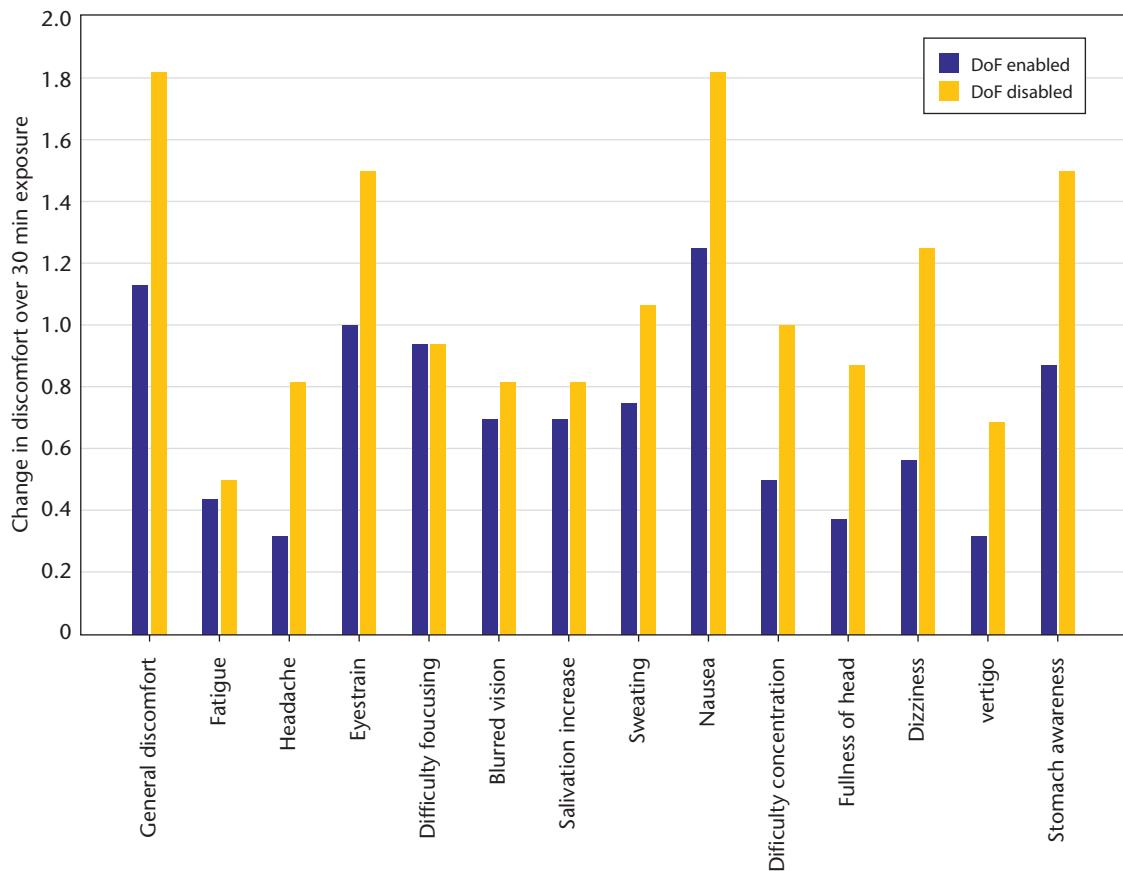
The participants were given minimal direction in what they were to do in the virtual scene; they were simply instructed to explore. This was done instead of specifying a track to follow because we wanted participants to move around the environments naturally. The participants were allowed to

withdraw from the experiment at any time if they felt sick.

## Procedure

The participants involved in the study were invited to two sessions on sequential working days. In the first session, the participants were shown the two scenes in random order, with DoF blur applied to one randomly chosen scene. In the second session, the DoF blur was applied to the other scene, and the ordering of the scenes was reversed. The number of participants whose first session had DoF blur enabled was equal to the number of participants whose first session had DoF blur disabled.

For this study, we used a Simulator Sickness Questionnaire (SSQ)<sup>8</sup> consisting of 18 questions. For each question, the participant was verbally asked about their current experience (symptoms), using a five-point Likert scale (ranging from "none," indicating no presence of that particular symptom, to "severe," indicating severe or traumatic presence). The SSQ responses resulted in an 18-part measurement of subjective discomfort across specific symptoms as well as a total sickness measure derived from the sum of the users' responses, multiplied by the weights used in earlier work.<sup>8</sup>



**Figure 7. Aggregate per-symptom results. The average of the participant responses for each symptom in our SSQ with DoF blur enabled and disabled.**

At the beginning of each session, the participants complete an SSQ. They then put on the Oculus and adjusted its physical settings so it was comfortable. The participants with glasses were given the option to wear them inside the Oculus if they could fit; otherwise, the appropriate lenses were put into the Oculus to compensate.

The nature of the control scheme was then explained to each participant. They were given a minute to become familiar with how the controls worked, and then they explored the presented scene for 15 minutes. An SSQ was then verbally completed. Next, the participants were asked to close their eyes, and we relocated them to the other scene, which they then explored for an additional 15 minutes before completing the third SSQ and taking off the Oculus. They were then asked to relax and wait for 15 minutes, before completing a final SSQ. Each SSQ was administered verbally.

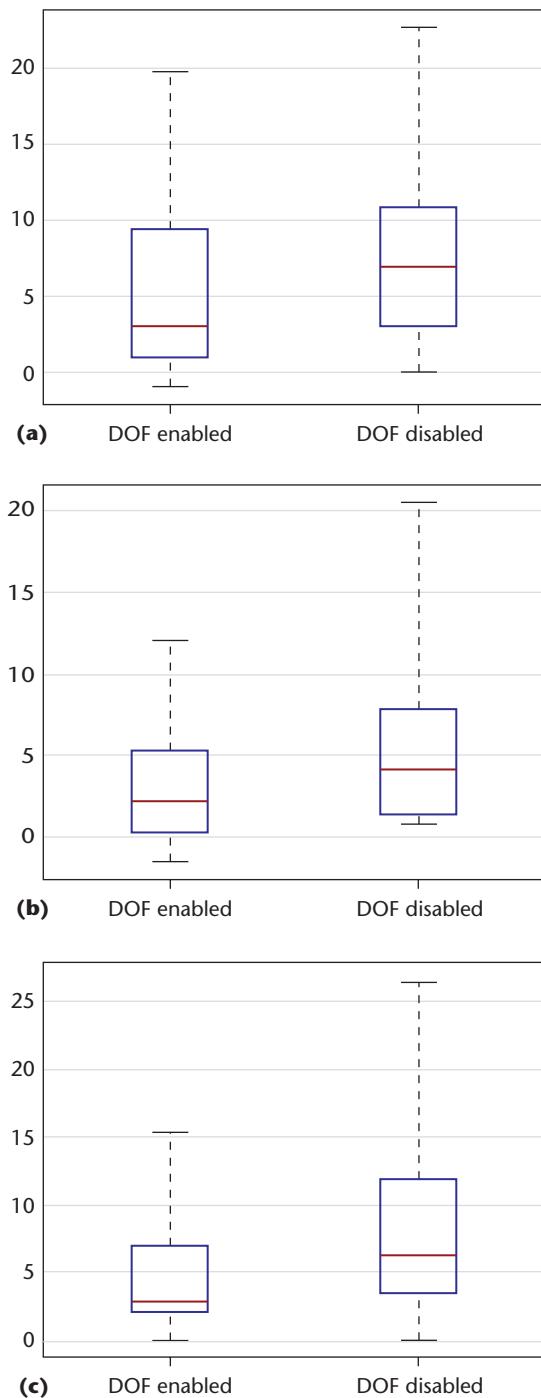
## Results and Analysis

In each session, we recorded four SSQ results: the initial response, following scene one, following scene two, and 15 minutes after the final exposure to the second scene on the Oculus. We subtracted the initial response from each of the three later responses to obtain a difference score for the se-

verity of each symptom (see Figure 7). The individual symptoms were multiplied by weights and summed to give the total sickness measure<sup>8</sup>  $S_T$  that the participant experienced during the session. The change in total sickness measure  $\Delta S_T$  was then used as a metric to determine visual discomfort on the HMD—a higher  $\Delta S_T$  indicates the user experienced a greater increase in discomfort during their session.

We observed a reduction in the mean  $\Delta S_T$ , from 21.46 to 13.58 when dynamic DoF blur was enabled. We also performed a Wilcoxon signed-rank test on  $\Delta S_T$  to establish whether this decrease is statistically significant. The results do represent a statistically significant reduction in mean discomfort ( $Z = -2.0684$ ,  $p = 0.01923$ ). We thus conclude that dynamic DoF is effective in reducing visual discomfort for general exploration activities in a VE on HMDs.

Based on previous studies, an effective system for reducing the contribution of the accommodation-vergence conflict on visual discomfort should reduce the screen area that is in focus at any given time, thereby reducing the amount of focusing a user needs to perform; reducing the range of virtual depths on which a user must focus; or minimizing the rate at which the user must adjust their



**Figure 8. Change of total sickness measure for each of the three discomfort categories: (a) Nausea, (b) oculomotor, and (c) disorientation.**

vergence. Our system was constructed to meet the first two of these conditions.

We observed a decrease in the mean sickness measure for each of the three discomfort categories.<sup>8</sup> Mean nausea discomfort decreased from 8.00 to 4.98, mean oculomotor discomfort decreased from 5.64 to 3.74, and mean disorientation discomfort decreased from 8.83 to 4.60 when DoF blur was enabled. Both of the decreases in

nausea and disorientation discomfort were statistically significant, with ( $Z = -1.8833, p = 0.03005$ ) and ( $Z = -2.103, p = 0.01786$ ), respectively. The decrease in oculomotor discomfort was weakly significant, with ( $Z = -1.3915, p = 0.08226$ ).

Six participants withdrew during our experiment, and every one of them did so in their first session when DoF blur was not enabled. We were not able to record and compare SSQ values for three of these users because of the severity of their symptoms. (They opted to not return for a second session or chose not to give answers due to the magnitude of their discomfort.) This significantly influences our results because we can thus only investigate the comparatively less severe SSQs.

Figure 8 shows the aggregate results for the participant's responses, split into these three categories, and Figure 9 shows the  $\Delta S_T$  scores with and without DOF enabled. The consistent decreases in discomfort symptom severity show that our system is effective at alleviating the accommodation-vergence conflict and its impact on visual discomfort.

Not all of the questions asked during our experiment were used to calculate sickness measures; we instead used anxiety and drowsiness responses to give a quantifiable estimation of a participant's mental state during the experiment. The results for loss of appetite and desire to move bowels were also not used because it was not feasible to control external factors, such as time since the participant had last eaten, which could significantly contribute to participant responses to these symptoms.

For general stereo displays (such as an LCD), limiting eye movement to only focusing on the center of a screen will limit users' spatial degrees of freedom. However, in HMDs, the majority of spatial movement will occur through head movements (changing the Oculus's orientation to look somewhere else) rather than through eye movements, compensating for this drawback. Effects such as variable acuity resolution on the Oculus, where central pixels are of a higher perceived density, also serve to drive user focus away from the periphery, limiting the effect of DoF blurring on peripheral information.

Of the 20 participants in this study, the six that withdrew did so during their first sessions when DoF was disabled, whereas none of the 10 participants whose first HMD exposure was with DoF enabled withdrew. Because all the participants had no prior experience with HMDs, this is a significant result: 30 percent of people trying this technology for the first time were so discomfited by

exposure that they felt unable to use it for half an hour. Adverse reaction rates this high are a serious issue for market adoption of HMDs. Our results show that rendering techniques such as DoF can effectively reduce this initial discomfort.

Two participants stated that they “felt equally sick on both sessions” and had consistent responses to their discomfort symptoms on each session. This indicates that there are people for whom DoF blur is not always relevant for reducing visual discomfort on HMDs. Thus, reducing the contribution of the accommodation-vergence conflict does not significantly affect their overall visual discomfort.

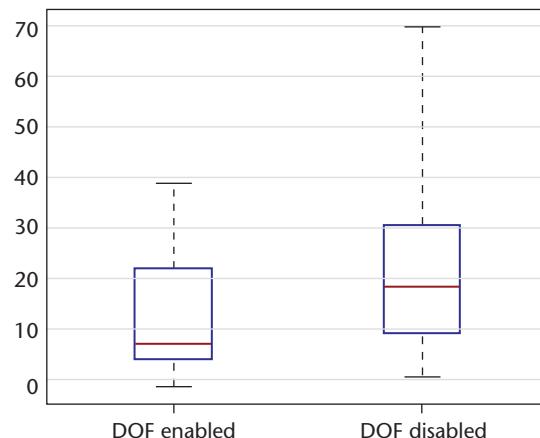
We used a common HMD, with display settings optimized for an average person and a mouse and keyboard control scheme implemented in many VR applications. Because this control scheme is not ubiquitous and the average settings will not work optimally for all users, further experiments should allow users more time to fine-tune the display and control settings.

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**Figure 9. Change of total sickness measure. (Left) With and (right) without DoF enabled.**

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