Thresholds of perceptual fatigue based on 3D object motion vectors and relative object size in virtual reality

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ABSTRACT

Over the past decade, Virtual Reality (VR) devices have not only emerged on the consumer market, but in various civilian and military use cases as well. One of the most important differences between the typical forms of VR entertainment and utilization in professional contexts is that operation may not be interruptible in case of the latter. For example, while the continuity of spatial surveillance and threat detection is indeed vital to the success and safety of tactical military scenarios, the operator may be affected by perceptual fatigue, particularly after extended periods of VR equipment usage. The same is applicable to both ground and air reconnaissance, as well as piloting and targeting. However, the thresholds of perceptual fatigue are affected by numerous human factors, equipment attributes and content parameters, many of which are not yet addressed by the scientific literature. In this paper, we present our large-scale study on the thresholds of perceptual fatigue for VR visualization. Five levels of fatigue are differentiated in order to examine the correlations between human perceptual endurance and the investigated test conditions in more detail. The experiments distinguish content based on motion vectors and object size relative to the space of perceivable 3D visualization. The majority of the exhaustive tests are analogous to the different zoom levels of visual capture equipment. Therefore, our work highlights optimal device settings to minimize the potential perceptual fatigue, and thus to support longer periods of uninterrupted operation.

Keywords: Virtual reality, perceptual fatigue, human factors, operation time, 3D object motion vector, relative object size

1. INTRODUCTION

Virtual reality (VR) technology is known for its rapid technical developments in the world of gaming and entertainment. VR also offers notable opportunities in numerous contexts, such as exhibitions of cultural heritage, education and training, human-computer interaction (HCI) and many others. In the healthcare sector, it is useful for medical treatment application, virtual rehabilitation, and surgical procedures. Generally speaking, 3D visualization technologies allow us to gain a better understanding of the design of complex structures (e.g., molecules, anatomical data, etc.), as well as virtual and real environments.[1] Moreover, VR is being used in professional and industrial contexts, such as the automotive industry and architecture. Therefore, research and development must carefully address a wide range of usage contents and human factors.

Roughly a decade ago, immersive virtual environment (VEs) were typically limited to the activities of experts in very specific application domains, such as training or simulation, or by test subjects during experiments.

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However, with the current technological and usage trends, it is rather obvious that in the near future, more and more people will spend a significant amount of their time particularly for communication and entertainment purposes in such immersive systems. Furthermore, in experimental contexts, these systems are mostly used for very limited amounts of time. In line with usage trends, experiments are now beginning to address longer periods of time.

In 3D applications, user task performance means the implementation quality of specific tasks, such as the time to navigate to a certain location or the accuracy of object placement. Task performance metrics may also be solely applicable to specific domains of defense applications. For example, evaluators may want to measure spatial awareness in a military training VE.[2]

Head-mounted displays (HMDs) generally consist of goggles with small screens, mounted in front of each eye and a motion-tracking system that monitors the position and movement of the user's head to be reflected in the virtual scene. Only the virtual scene is perceived while wearing the HMD, and all movements of the user in the real world – such as walking or head movements – are transferred to corresponding motions of the virtual camera, thereby an updated virtual view is provided.[3] The military places HMDs in the aircraft cockpits and in many kinds of vehicles.[1,4]

However, the use of stereoscopic display systems also has serious drawbacks. An elemental problem that must be considered when creating VR environments is that adverse symptoms may occur during VR use. Numerous works in the literature analyze the main disadvantages of stereoscopic 3D technology. The human perception of depth is based on a variety of visual cues, as well as inner mental templates and expectations.[5] If the 3D signals in a stereography presentation are inconsistent with others, conflicting information is received by the perceptual system and thus it seeks a consistent interpretation. If severe conflicts occur, the 3D perception of the scene may be completely disrupted or become highly inaccurate. The effort is taken to resolve conflicts can induce serious fatigue, eyestrain, and headache, and may degrade the sense of immersion.[1] Furthermore, the viewer might experience more severe symptoms of visual fatigue in case of stereoscopic scenes because of its vivid feeling of reality than in case of conventional 2D visualization.[6]

Visual fatigue is comprised of a wide range of symptoms, including tiredness, headaches, and the soreness of the eyes. It can be caused by focusing the eyes on a near object, and may also involve central cortical structures, for instance, those involved in viewing a wide-angle, high-contrast, geometric pattern.[7]

Factors of the visual experience among others include changes in size and brightness, geographical perspectives (i.e., topographical features), and the distribution of shadows and lights. The distance between the viewer and a visual target cannot be estimated directly by a simple measure, whereas it can be recognized by the cortical processing of these diverse visual cues. Among these, binocular disparity is the most important, because it is the only mechanism to provide depth information in commercially-available systems. The unconscious efforts to resolve the conflict would cause visual fatigue.[6]

In this paper, we introduce the results of a series of subjective tests on the perceptual fatigue induced by VR visualization. We particularly addressed motion directions and the relative size of the moving object (i.e., zoom level) in the VR content to measure their effects on the temporal progression of exhaustion. We differentiated five levels of fatigue, from which the most important ones were the transition between the first two levels (i.e., the first self-perceived symptoms of fatigue) and the last level (i.e., at which the test was aborted due to perceptual exhaustion).

The remainder of the paper is structured as follows: Section 2 reviews the relevant scientific literature. Section 3 introduces the experimental setup of the research. The obtained results are provided in Section 4, extended by discussions in Section 5. The paper is concluded in Section 6.

2. RELATED WORK

In the last couple of decades, a significant number of papers have been continuously discussing human factor issues associated with VR. Despite rapid developments in VR technology (i.e., the improvement of consumer-grade and professional end-user devices), a considerable portion of users still experience VR-induced symptoms and health problems; however, for the majority, these effects are mild.

Kooi and Toet[1] empirically determined the level of discomfort experienced by an observer in 14 factors by a series of subjective tests, using a 5-point assessment scale. Some studies indicate that after experiencing VEs, the reported motion sickness is more significant when both pre- and post-questionnaires are given than when only a post-questionnaire is used.[8,9] The results of another experiment suggest that the positioning of users in VEs may also affect susceptibility to sickness.[10] For example, a sitting position may reduce sickness symptoms, as this reduces the demands on one's postural control.

In a multi-user collaborative VE, active users have been found to be less susceptible to sickness than passive users.[11] Stanney and Hash[12] also found similar results. In their experiment, when users were able to control their own movements, the sickness symptoms were less severe than when users had no control over their movement. Furthermore, McCauley and Sharkey[13] distinguished the effects on the user of "near" and "far" applications. Nearby applications − such as virtual imaging of medical procedures − contain only limited head movements and lack full-body rotation and linear acceleration. In contrast, the motion present in far applications − such as terrain examinations and vehicle simulators − results in a greater probability of a lack of corroboration of visually represented motion with vestibular signals.[10] Therefore, the authors concluded that motion sickness is only to be expected in far applications, unless near applications require excessive head movements. It has also been suggested that pilots are less sensitive than the general population because of "self-selection". Thus, the prevalence in the general population may be higher than previously observed in studies using the military population.

Only a few papers discuss the long-term use of such a fully-immersive technology. Steinicke and Bruder[3] conducted a self-experiment in which they exposed a single participant for 24 hours to a fully-isolated virtual world, and applied different metrics to analyze how human perception, behavior, cognition, and motor systems change over time. The subjective level of comfort was assessed on a 5-point Likert scale, ranging from very uncomfortable to very comfortable. Serious simulator sickness symptoms were reported by the participant, which varied over time with the participant's activities. The results show that with long exposure to VR, undesired side effects emerge.

In addition, Marucci *et al.*[14] performed Electroencephalography (EEG) and Galvanic Skin Response (GSR) measurements during their realistic VR experiments to investigate how multisensory signals impact target detection in two conditions: low and high perceptual load. Different multimodal stimuli were presented alone or in combination with the visual target simultaneously. The results showed that the high multisensory stimuli significantly improve performance, compared to visual stimulation alone. Overall, these findings provide interesting and useful insights into the relationship between multisensory integration and human behavior and cognition.

3. EXPERIMENTAL SETUP

3.1 Hardware and software components

The experiment was carried out using an HTC Vive Pro[*] headset. It was selected for its wide adoption in industrial VR applications, as well as the high-resolution 2880 × 1600 (combined) AMOLED screens and its highly adjustable design. Adjustability was particularly important, due to the different head shapes and design constraints inherent to the form factor of these headsets. The eyes have to be in a very specific position in relation to the lenses in order to get a distortion-free image.

The environment for the experiment was created using the Unity[†] game engine. As a general 3D engine, it is widely used in many areas from gaming to film production, and features support for all major VR headsets. The environment was designed to be visually "uninteresting" (i.e., there was nothing particularly stimulating) to not distract from the experiment at hand. A cube was chosen as the moving object. The application was run on machines with Nvidia RTX 2060 GPUs and Intel 8th generation I5 CPUs which well exceed HTC's recommended specifications for the Vive Pro and could run the software at the headset's native 90 Hz refresh rate.

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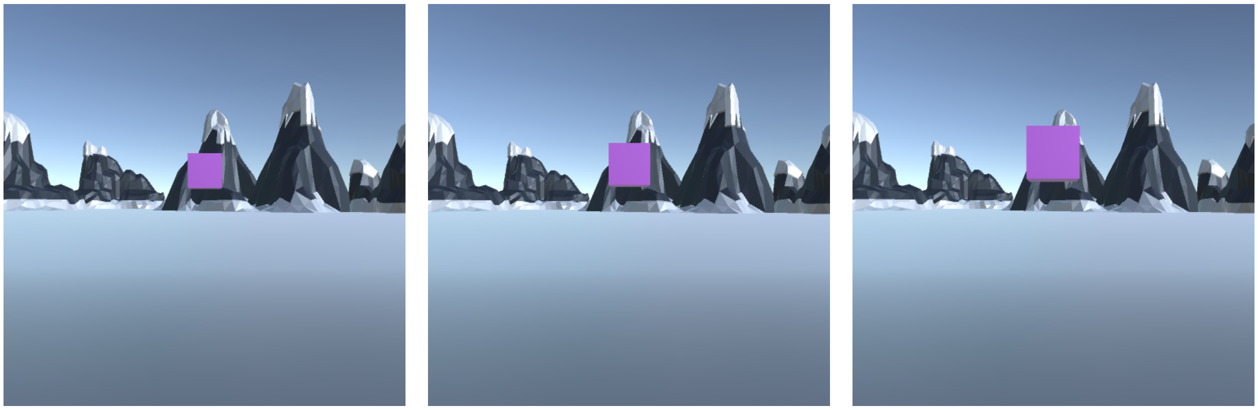
[*] https://www.vive.com/us/product/vive-pro/

[†] https://unity.com/



(a) Zoom level 1 (b) Zoom level 2 (c) Zoom level 3

Figure 1: Frames from the 3 virtual scenarios of the different zoom levels perceived by the test participants when wearing the headset.

3.2 Test environment

The subjective tests were carried out in a laboratory environment, isolated from external audiovisual distractions. While wearing the headset, the test participants could only see the VE, and were isolated from any distracting noise using disposable earplugs. In order to eliminate fatigue from sources other than the experiment, test participants were seated in office chairs where they could relax themselves during the experiment. The environmental conditions were as calm and homogeneous as possible.

3.3 Test conditions

The test variables of the experiment were the motion patterns of the object and the zoom levels of visualization. Each of them had 3 different settings. As we employed a full combination of the test variables, there was a total of 9 test conditions. The chosen motion patterns were horizontal, vertical and 45 degrees diagonally to the left. In the different zoom levels, the distance of the cube was increased by 2 meters for every level starting from 8 meters as seen on Figure 1. The $1\,m \times 1\,m$ large cube moved at a constant speed between the ends of its path and changed direction instantaneously in all directions and zoom levels. The length of the path the cube travels was chosen such that it does not extend to the very edges of the headset's field of view, as distortion from the lens is very apparent and distracting in those regions. The colors used in the environment, as well as the cube were also selected to be the least distracting they could be. The low-poly mountains were also chosen for this reason.

3.4 Experimental methodology

VR environments may cause users to experience sickness, visual fatigue, and disorientation. The methodology for the assessment of general perceptual fatigue was inspired by the 5-point Degradation Category Rating (DCR) scale[‡]. It measures two perceptual components: detectability and the subjective toleration of degradation. The 5 points of the scale are the following: *Imperceptible* (5), *Perceptible but not annoying* (4), *Slightly annoying* (3), *Annoying* (2) and *Very annoying* (1). Technically, the discrimination of 5 and 4 determines whether an artefact or degradation is perceivable or not, and the remainder of the scale reports the extent of annoyance. In our subjective test, rating was analogous in the sense that the transition between 5 and 4 signified the first emerging sensations related to fatigue, and the rest assessed its progression over time. When a test participant reached 1, the test was aborted. The maximum duration of the test was 30 minutes; the test ended after 30 minutes if the test participant had not reached 1 on the scale by then. The ratings were reported verbally, which was registered by the research team, quietly situated in the same environment. Whenever a number was reported, the time passed since the beginning of the experiment was recorded.

[‡] https://www.itu.int/rec/T-REC-P.910

As mentioned earlier, the test participant was seated during the test. Additionally, during the training phase, the test participant was instructed to avoid unnecessary motions and the assessment scale was thoroughly explained and practiced in order to avoid misunderstandings and errors.

In the experiment, we presented each observer with only one of the 3 scenarios. It is important to highlight that a specific test participant only completed 1 of the 9 test conditions.

3.5 Participants

A total of 34 test participants completed the experiment. 17 were male and 17 were female. The age of the test participants ranged between 20 and 51. As there were 34 test participants and 9 test conditions, each test condition was completed by either 3 or 4 test participants. The test participants were screened for normal vision and color vision prior to the experiment.

4. RESULTS

The results of the experiments regarding the three different zoom levels are shown in Figure 2. The proportional decrease of the data range can be observed with the increasing zoom level of the object. The third degree of zoom setting resulted in a higher time average corresponding to the transition from 5 to 4 on the assessment scale.

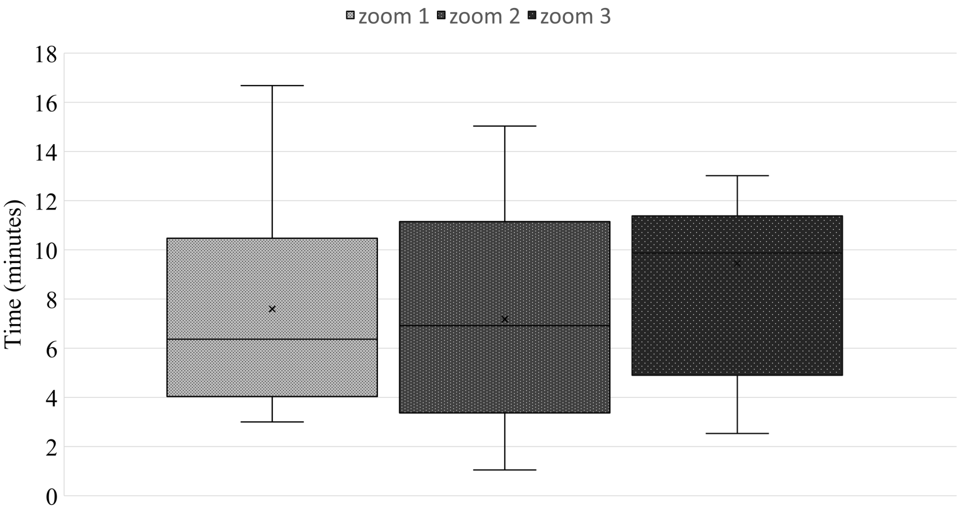


Figure 2: Data from the 3 investigated zoom levels.

As far as the three examined motion directions are concerned, the average time when participants still experienced the initial comfort with no sign of perceptual fatigue is between 6 and 9 minutes for all three settings as can be seen in Figure 3. The range was the widest for the diagonal setting.

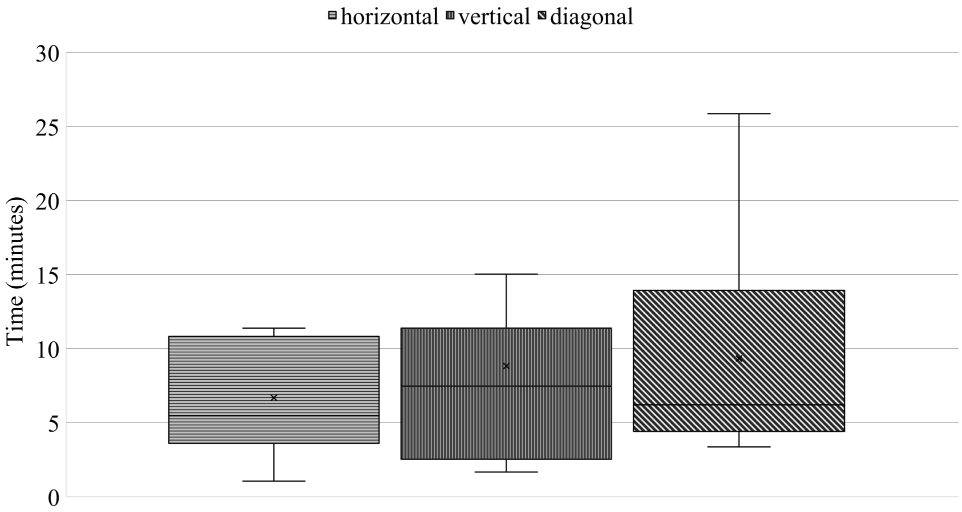


Figure 3: Data from the 3 investigated directions.

Figure 4 shows the distribution histograms for all 34 participants at the time of transition from 5 to 4 on the assessment scale and the time when the experiment stopped. The data is sorted according to the onset of fatigue indicated by the participants in order to examine the time elapsed between the initial and final states. Overall, the end times of the use of VR goggles typically follow the initial values in descending order.

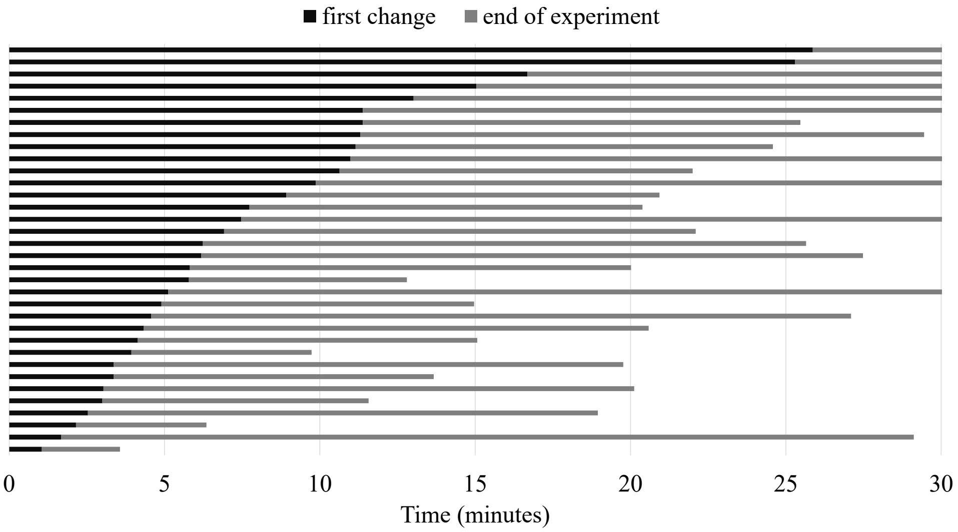


Figure 4: Progression of perceptual fatigue over time.

To provide more insight into the data, the results grouped by zoom level and direction of movement are shown graphically in Figure 5 The average time before the perceptual fatigue appeared is generally between 5 and 10 minutes for 7 test conditions. In comparison, this value is lower at zoom level 2 and higher at zoom level 3 for diagonal movement. The greatest difference between the minimum and maximum values can be observed for the vertical direction at zoom level 2 and the diagonal direction at zoom level 3.

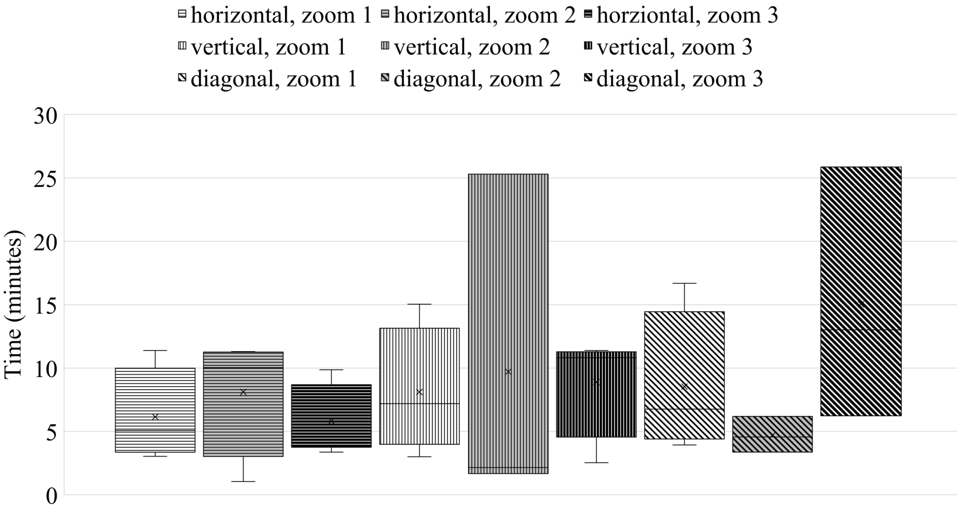


Figure 5: Data from all permutations of directions and zoom levels.

5. DISCUSSION

The data from the setting of the three different zoom levels show that in the case of zoom level 3, the test participants had a slightly higher tolerance of near objects moving in the VE. The time when the participants indicated the perception of fatigue did not show a statistically significant difference. However, notable variations are seen at this starting point, which indicates that diagonal motion is of particular significance. This is consistent with the phenomenon shown in Figure 5. Participants reacted differently to this direction of movement than to the horizontal and vertical movements that can be called customary.

Limitations of the study include the fact that the Vive Pro headset was the only model available to the test participants. The varying comfort and adjustability of other headsets could influence the level of fatigue experienced over time. In addition, while our experiment was silent, audio could influence fatigue as well. In the future, even more variables could be evaluated, such as the speed of the moving object.

There is a notable limitation regarding the experimental methodology as well. While the 5-point DCR scale does provide an appropriate method for measuring perceptual fatigue, it is nonetheless a self-reported subjective score. The primary issue with this fact is that in certain utilization contexts, endurance is absolutely essential. This particularly applies to the military. Basically, test participants may feel the pressure to perform well, which may lead to significantly delayed transitions on the scale. Such a bias is also worthy of future investigation.

6. CONCLUSION

In this paper, we investigated the thresholds of perceptual fatigue for VR visualization. We aimed to characterize the level of discomfort induced by the visualized content in the user over time. The study highlights how object motion and zoom levels may affect visual comfort. The test participants were exposed to the VE for a maximum of 30 minutes, and based on the obtained results, we can conclude the following.

The different user reactions we observed to the different experimental settings suggest that the direction of motion and the zoom level of the perceived object play a significant role in user experience with HMD. Multiple aspects regarding the use of VR headsets need to be further investigated, such as the relationships between subjective user experience and additional objective measurements. Including, but not limited to, the following tests would be appropriate: continuous heart rate and Galvanic Skin Response (GSR) measurements, as well as electroencephalography (EEG). Furthermore, the investigation of the impact of multisensory stimuli on the quality of task performance – in addition to the settings we have already tested – is advised.

With the rise of new immersive technologies, more and more people are using these systems for longer and longer periods of time. The investigation of the test conditions described earlier suggests that VR headsets have great potential for employment in various defense applications as well, especially in management and monitoring tasks. Our findings show some shortcomings and open challenges, which need to be addressed in order to increase the efficiency of long-term usage.

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