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Comparison of visual discomfort when viewing 3D videos with various contrast changes on a stereoscopic 3D display, an auto-stereoscopic display, and an HMD

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Abstract

The increasing popularity of different kinds of 3D displays such as stereoscopic 3D monitors, auto-stereoscopic displays, and head mounted displays (HMDs) has led to visual discomfort being considered as one of the major concerns in the 3D industry. Previous research studies on visual discomfort have considered various disparities and motions in 3D videos to identify vergence-accommodation linkage conflicts. In this paper, we measure visual discomfort occurring from viewing 3D videos with various contrast changes using perceived symptoms questionnaires, measured near point of convergence, eye blink rate, and saccadic movements. We compare visual discomfort for different displays such as stereoscopic 3D (s3D) display, auto-stereoscopic display, and HMD. From our experimental results, we conclude that visual discomfort increases when the subject is watching 3D videos using auto-stereoscopic displays. In addition, brighter videos caused more visual discomfort compared to darker videos.

Introduction

Recent advancements in 3D displays and head mounted displays (HMDs) have raised research interest in virtual reality and augmented reality. Unfortunately, watching 3D content causes visual discomfort. This is primarily due to the vergence-accommodation linkage conflict, which is a mismatch between the point of interest and focus point of each eye when images are projected on the retina [1-2]. Besides the vergence-accommodation linkage conflict, factors such as changes in saturation, brightness, motion-in-depth, and disparity can also lead to visual discomfort [3-8].

The most common types of 3D displays for watching 3D content are stereoscopic 3D (s3D) monitors, auto-stereoscopic 3D monitors, and HMDs, all of which utilize s3D [9-11]. s3D is a mechanism that displays two different views to the left and right eye to create a 3D effect. The 3D monitor has two types of 3D systems: shutter-glass and polarized. In the shutter-glass 3D system, an image is presented to one eye while blocking the other eye and vice versa for the next image while the left and right images are displayed alternatively. The polarized 3D system incorporates polarization glasses to restrict light that reaches each eye, thus differentiating the image on each eye to create a 3D image. The auto-stereoscopic 3D monitor also uses two types of mechanisms: parallax barrier and lenticular lenses [9-12]. The parallax barrier mechanism places a barrier with slits in front of the display to provide both eyes with different views, whereas the lenticular lenses mechanism places an array of lenses in front of the display to provide different views to each eye. Finally, the HMD presents two views adjusted to each eye [9-10].

The s3D monitor and auto-stereoscopic 3D monitor are commonly used to watch movies, dramas, or sports games. In addition, HMD is widely used in virtual reality or augmented reality domains such as in games and simulations. Because the s3D monitor, auto-stereoscopic 3D monitor, and HMD utilize the s3D mechanism, the viewer experiences visual discomfort including headaches or dizziness when viewing 3D content.

In this paper, we analyze the visual discomfort caused from viewing 3D videos on a s3D monitor, an auto-stereoscopic 3D monitor, and an HMD using eye-blink, saccadic movement, and near point of convergence (NPC). For our experiment, we used three videos in which objects were positioned at the comfort zone having various contrast changes. In order to detect human visual discomfort, we measure each subject's eye blink rate, saccadic movement, NPC, and conduct surveys before and after the experiment.

Related Works

Previous research on visual discomfort were mostly performed on various disparities and motions in 3D video to deal with vergence-accommodation linkage conflicts [1-2]. Vergence-accommodation linkage conflicts occur when eyes are controlling and congesting at the same time, causing the point of interest and focus point to misalign when viewing 3D content. The change in motion-in-depth and disparity are other reasons for visual discomfort because both motion-in-depth and disparity factors are related to the vergence-accommodation conflict [3-5]. Finally, the brightness of the image is another factor that causes visual discomfort [6-8].

In particular, visual discomfort when viewing 3D video using s3D monitors has been analyzed thoroughly. However, with the expansion of the 3D displays industry, new 3D devices such as auto-stereoscopic displays and HMDs have become popular. Therefore, it is necessary to extend the research to explore visual discomfort caused from viewing 3D content on these devices. Furthermore, it is important to measure visual discomfort caused from watching 3D videos with various contrast changes.

Because an auto-stereoscopic 3D monitor does not require the use of 3D glasses, it is mostly used in mobile displays. However, mobile displays are not stationary but in motion, and therefore, they are more likely to cause greater visual discomfort than other 3D displays [13]. Though many mobile displays have different sizes, most mobile 3D displays can handle the reduced range of the uncertainty of 3D content [14].

When using HMDs, headaches are a common symptom due to the misalignment of information received by the user's vestibule organ and the perception of image presented by the HMD [15-18]. Moreover, watching unnatural motions presented by the HMD may make the audience feel uncomfortable [19].

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Experimental Design

We designed our experiments to measure and analyze the visual discomfort caused by each type of 3D displays (27-inch stereoscopic 3D monitor, 25-inch auto-stereoscopic 3D monitor, and an HMD). A total of 23 subjects (14 males and 9 females; average age: 23.15 years) participated in this experiment. However, two subjects were excluded because they were unable to watch 3D content, and another subject was excluded because the subject's head movement and sleeping interfered with the data.

For the s3D monitor and auto-stereoscopic 3D monitor, we recorded each subject's eye movement by measuring eye blinks and saccadic movement; the eye movement was measured using EyeLink 1000 plus. However, because the HMD is attached in front of the subject's face, it is difficult to measure the subject's eye movement. Therefore, we measured NPC and conducted a survey to determine visual discomfort. The survey includes eight questions listed below; they are similar to those in [3]. Each subject answered the question using a 5-point scale from 1, which represents "completely disagree" to 5, which means "completely agree."

Q1. My eyes feel tired.
Q2. My eyes feel dry.
Q3. I see a double image.
Q4. I have blurred vision.
Q5. I feel dizzy.
Q6. I have a headache.
Q7. I feel fuzzy.
Q8. My eyes are stressed.

Because the survey results are only a subjective judgment, we measure NPC before and after the experiment. For accurate measurements, we make three videos by changing the brightness of the object in the videos. The object is located within the comfort zone [20]. The object is positioned at -1 degree of disparity throughout the video to reduce visual discomfort caused by disparity and image distortion. The videos are 20-min long. Figure 1 shows our test videos similar to [7].

The experiment procedure is shown in Figure 2. First, the subjects answer the survey and their NPC is measured. Then, the subjects watch a 20-min test video and their eye movements are recorded while they are watching the video. Next, the subjects answer the survey and their NPC is measured once again. Here, we record the subjects' NPC before answering the survey because NPC can be recovered while subjects are answering the survey. After answering the survey, the subjects take a 10-min break for recovery. We check subjects' recovery of eyes by comparing NPC recorded before and after watching the test video. When subjects' eyes are fully recovered, we change the test video or display and repeat the procedure until the subjects watch three test videos from three different types of monitors. Figure 3 shows our experimental setup.

Experimental Results

We analyzed visual discomfort using the measured eye blink rate, saccadic movement, NPC, and the survey results. Because it is difficult to measure eye movements for HMD, we only measured NPC and conducted a survey to analyze the visual discomfort.

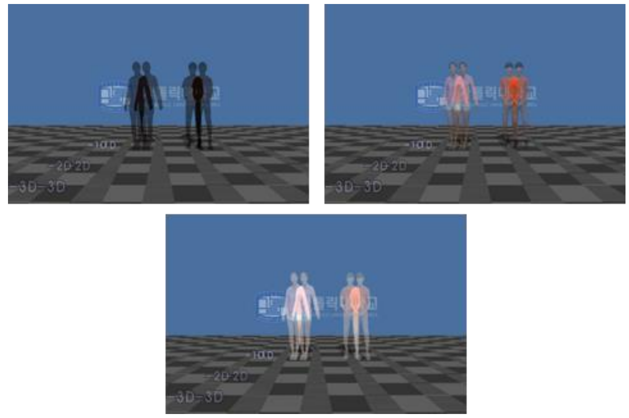

Figure 1. Test Videos

Figure 2. Test Procedure

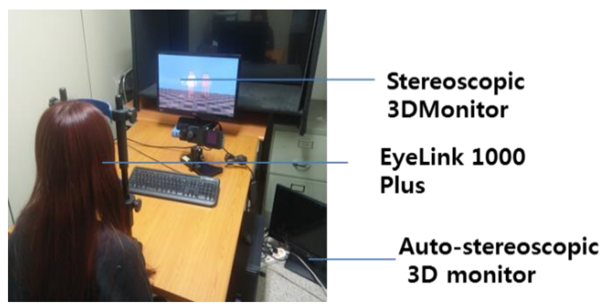

Figure 3. Experiment Environment

Eye-Blink Rate

We measured eye blink rate using EyeLink 1000 plus. As the image gets brighter, the eye blink rate increases slightly. The eye-blink rate when watching the test video on the auto-stereoscopic 3D monitor was higher than watching the video on the s3D monitor. Usually, the eye-blink rate increases when eyes are tired. Thus, the auto-stereoscopic 3D monitor causes more visual discomfort than the s3D monitor. Figure 4 shows the number of eye blinks.

Saccadic Movement

Using Eyelink 1000 plus, we analyzed the saccadic movement rate that indicates eye movement. As the image gets brighter, saccadic movement decreases. We found that saccadic movements decreased more in the case of watching 3D video from the auto-stereoscopic 3D monitor compared to the s3D monitor. The decrease in the saccadic movement implies that the eyes are tired. Thus, the audiences feel more visual discomfort when watching s3D content through the auto-stereoscopic 3D monitor. Figure 5

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shows saccadic eye movements for the s3D and auto-stereoscopic displays.

NPC

The NPC value refers to the subjects' ability to converge their eyes. To recognize s3D videos as three-dimensional, the subjects need to converge their eyes. As the subjects converge their eyes constantly when watching 3D videos, the stress on the eyes increases, affecting the subjects' ability to converge their eyes effectively. NPC values increased after watching s3D videos on the three types of monitors. The NPC value changes were the greatest when watching through the auto-stereoscopic 3D monitor. The NPC value changes were the least when watching through the s3D monitor. The value change of NPC of the auto-stereoscopic 3D monitor, the HMD, and the s3D monitor are 1.9 cm, 1.5 cm, and 1.3 cm, respectively. The subjects feel the most visual discomfort when watching the s3D video on the auto-stereoscopic 3D monitor and feel the least visual discomfort when watching it on the s3D monitor. Further, because the increased NPC value indicates that the human's ability to converge eyes decreases, in extreme cases, the subject may see two non-overlapped videos instead of recognizing as 3D.

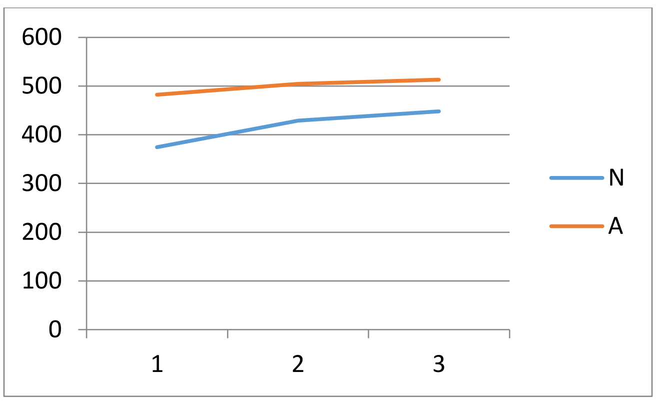

Figure 4. Average Number of Eye blinks for each test video (N: s3D monitor, A: Auto-stereoscopic 3D monitor)

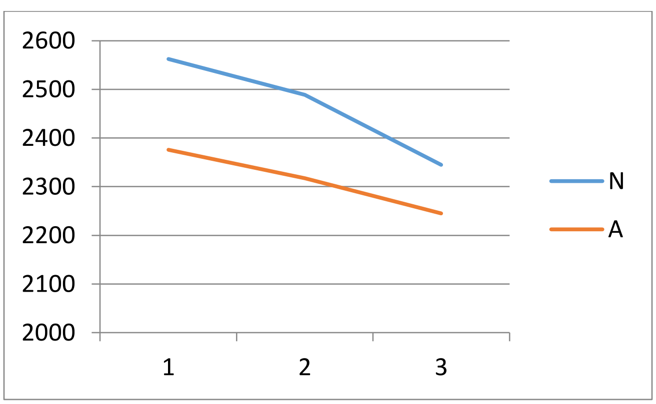

Figure 5. Average Number of Saccadic movements for each test video (N: s3D monitor, A: Auto-stereoscopic 3D monitor)

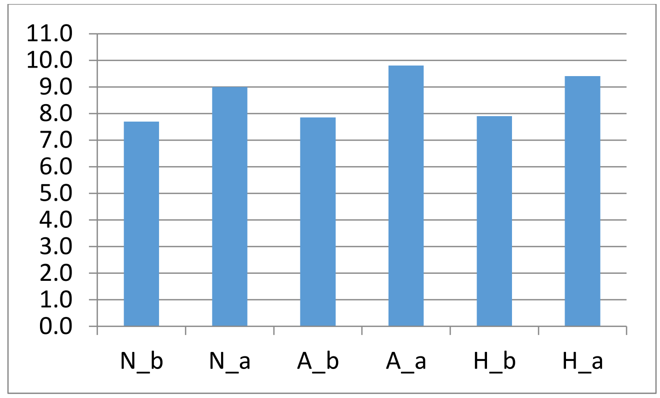

Figure 6. Average NPC values before and after watching video (N: s3D monitor, A: Auto-stereoscopic 3D monitor, H: HMD, a: before watching video, b: after watching video, y-axis: cm)

Survey

The subjects answered the survey using a 5-point scale from 1 to 5 before and after watching the video. The survey questionnaire results were calculated by subtracting the values of post-experiment survey from the values of pre-experiment survey.

Figure 7 shows our survey results. Q1 and Q2 are related to eye tiredness and dryness. The value of Q1 is the greatest for the auto-stereoscopic 3D monitor and the least for the s3D monitor. The value of Q2 is the greatest for the HMD and the least for the s3D monitor. The auto-stereoscopic 3D monitor and HMD cause more visual discomfort than the s3D monitor.

Q3 and Q4 are related to double image and blurred vision. The values increase for all three displays with a slight difference between each display. The double-image occurs because of the afterimage of s3D videos.

Q5 and Q6 are related to headaches or dizziness. The values of Q5 and Q6 are the greatest for the auto-stereoscopic 3D monitor and the least for the s3D monitor. Because of the 3D quality of the auto-stereoscopic 3D monitor, it can be assumed that the subjects experience dizziness and headaches. Although the HMD incorporates a similar mechanism as the s3D monitor, the small distance between the display and eyes, the lack of outside light, and un-alignment between body movement and object movement in the video cause dizziness and headaches that are similar to carsickness.

Q7 and Q8 cover fuzziness and stress. Both Q7 and Q8 have the greatest value for the HMD and the least value for the s3D monitor.

For each display, we analyzed eye-blink rate, saccadic movement, NPC, and survey. The results for eye-blink rate, saccadic movement, and NPC indicate that the subjects feel the most stressed when watching 3D content on the auto-stereoscopic 3D monitor and the least for the s3D monitor. The result of the survey varied for each question; however, this difference stems from the subject's subjective judgment. The s3D monitor was the most comfortable for viewing 3D content; however, it was the auto-stereoscopic 3D monitor—not HMD—that caused the most visual discomfort.

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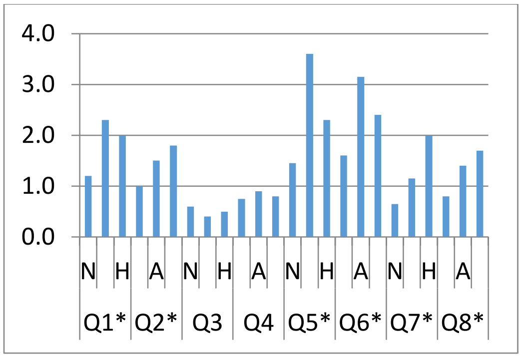

*Figure 7. Survey Questionnaire results (N: s3D monitor, A: Auto-stereoscopic 3D monitor, H: HMD, x-axis: questionnaire number, y-axis: score difference between before and after test), (*p<0.05).*

Conclusion

In this paper, we analyzed visual discomfort occurring from watching s3D videos on the s3D monitor, auto-stereoscopic 3D monitor, and HMD. We measured eye-blink rate, saccadic movement, NPC, and conducted a survey for analysis. For HMD, we only used NPC and subject survey because it is difficult to measure the eye movement.

The results of eye-blink rate demonstrated that watching 3D videos on the auto-stereoscopic 3D monitor is more uncomfortable than watching it on the s3D monitor because of higher eye blink rate. Saccadic movement was greater for the s3D monitor than for the auto-stereoscopic 3D monitor, reinforcing that subjects feel more visual stress when watching through the auto-stereoscopic 3D monitor. The change of NPC value was the highest for the auto-stereoscopic 3D monitor and the smallest for the s3D monitor. Each question of the survey had different results; for Q1, Q5, and Q6, the auto-stereoscopic monitor had the greatest value while the s3D monitor had the least value. In Q2, Q7, and Q8, HMD had the greatest value and the s3D monitor had the least value. For Q3 and Q4, there were no significant differences between the displays.

From our experiments, the auto-stereoscopic 3D monitor is the most tiresome, HMD is less tiresome, and the s3D monitor is the least tiresome display. However, because eye-blink rate and saccadic movement were not measured for HMD, different methods to accurately measure the visual discomfort will be necessary in future studies.

For HMD to become the next leading display, the critical factors that cause visual discomfort need to be eliminated. Research on exploring and verifying the reasons for visual discomfort caused from HMD should be continued. Further, we plan to extend our work to reduce visual discomfort when viewing 3D content on the HMD.

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