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Analysis of blue-light effects in reducing visual discomfort from watching stereoscopic 3D video

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Abstract

Various researches identified that the main factors causing visual discomfort from watching 3D video are Vergence-Accommodation linkage conflicts, contrast changes, and some other defects in 3D display. In this paper, we propose a new method to lessen the visual discomfort by reducing blue-light components, which are highly sensitive to human eyes in 3D video. In our experiments, 20 people (9 male, 11 female) participated in watching four 15-minute original and blue-light reduced modified 3D videos, respectively. We surveyed perceived symptom questionnaires before and after watching videos, and measured the participant's eye-blink rates, saccadic movements, and near point of convergence (NPC). Our experimental results demonstrated that the eye-blink rate of the participant was lower in watching the blue-light reduced videos, while saccadic movements of the subject was higher in blue-light reduced videos compared to the original videos. Since eye-blink rate is usually increased when subject's eyes are dried, and slower eye movements are occurred due to tiredness, the blue-light reduced video caused smaller visual discomfort than the original video. Based upon NPC and perceived symptom questionnaires, we confirmed that viewers indeed feel more comfortable watching the blue-light reduced video compared to the original video.

Introduction

Public interest in 3D content has increased with the release of many 3D movies, and with HMD (Head Mounted Display) signaled as the next-generation display. Watching 3D content can cause eyestrain, headaches, and dizziness. Many people experience discomfort when watching 3D content, and some people cannot watch such content continuously [1]. Many studies have been conducted in order to reduce such symptoms. Vergence-accommodation conflict is the main cause of visual discomfort [2-4]. When a person watches s3D (stereoscopic 3D), vergence and accommodation occur simultaneously, thus allowing the person to recognize the 3D image [5-7]. Vergence is the process of combining two 2D images into a single 3D image, and accommodation is the movement of focus. During this process, people can experience eyestrain and eye dryness, headaches, and dizziness because of vergence-accommodation conflict. Such conflict occurs because the vergence point of the two eyes and the accommodation point do not match. In addition to the vergence-accommodation conflict, disparity changes, motion-in-depth, contrast, brightness, and distortion are some other causes of visual discomfort when watching 3D content [8-14]. However, beside the aforementioned factors, research on blue-light, which causes eyestrain and dryness, is also an important factor in causing visual discomfort.

Blue-light is the portion of the visible spectrum that ranges from 380 nm to 500 nm, and it radiates from computer monitors and smartphones. Photochemical retinal damage caused by blue-light can deteriorate eyesight, and can even cause blindness [15]. The dangers from eyestrain and dryness, as well as retinal damage from blue-light, are not new [16-18]. However, warning and caution messages about blue-light have been targeted only at those exposed to luminous sources, such as light-installing engineers and welders [19]. Messages about the dangers from blue-light started to be introduced to the general public with the distribution of LEDs with high blue-light ratio. When LEDs were first commercialized, they were a source of light that radiates red light low in brightness. Recently, however, the development of high-brightness and high-power LEDs has exposed people to the increased dangers from blue-light.

Many studies have been conducted on the danger of being exposed to blue-light for an extended period. However, research on the visual discomfort that results from watching video is also required. Greater visual discomfort is caused from short waves [20]. Here, "short waves" refers to blue-light.

In this paper, we analyze the effects of blue-light in visual discomfort while watching 3D content. Conventional research on blue-light has analyzed retinal damage, sleeping disturbances, and fatigue caused by long-term exposure to blue-light. However, there is insufficient research on the effects of blue-light while watching video. The purpose of this research is to verify the following:

1. Visual discomfort caused by blue-light while watching 3D video.
2. Whether visual discomfort decreases when reducing the amount of blue-light.
3. Blue-light effects on 3D-content recognition ability.

Eye-blinks, saccadic movements, and surveys used in conventional research to measure visual discomfort are used to monitor the effects of blue-light on visual discomfort while watching 3D content. Then, NPC (Near Point of Convergence) is used to monitor visual discomfort and 3D-content recognition ability. Four videos with removed blue-light are developed by adjusting the color temperature. An eye-tracking device measures eye-blinks and saccadic movements while subjects watch videos, and NPC measurements and surveys are conducted before and after watching video.

Experimental Design

Experimental Setup

Studies on the negative effects of long-term exposure to blue-light are important, but the visual discomfort experienced by viewers while watching video is also crucial. However, to the best of our knowledge, not much research has been conducted on the visual discomfort caused by blue-light while watching video. In order to measure such discomfort, eye-blinks and saccadic movements are measured. Furthermore, NPC is measured and surveys are conducted before and after watching video.

A stereoscopic 3D monitor was used, and the experiment was conducted by reducing blue-light from s3D videos. A 27-inch

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monitor with 16:9 aspect ratio and spatial resolution of 1920×1080 pixels was used.

A total of 20 subjects with ages that ranged from 20 to 28 years participated in the experiment. Of the 20 subjects, 9 were male and 11 female. The subjects watched the monitor seated a distance of 2014 mm from the monitor. Such distance was determined based on the recommendations of ITU-R BT. 500-13 [21]. In order to exclude any effects from external factors, the room temperature and humidity were set at a certain level. The subjects watched the video in a dark room individually, and the only illumination was generated from the monitor.

EyeLink 1000 plus was used to track eye movement. To use this device, the subject rests his or her chin on the chin-rest and watches the video. While watching the video, EyeLink records and saves the subject's eye movement. EyeLink 1000 plus records data that includes the x-coordinate and y-coordinate of the point where the eye stops, time, eye-blinks, saccadic movements, and fixation.

Figure 1. Experiment setup

Test Video

We developed 3D videos for the experiment because we could not find appropriate videos that eliminated blue-light. The video source from the past experiment was used, and blue-light was removed from the video. The video was developed so that the objects were located at the comfort zone [22]. Disparity of -1 degree was used in order to reduce the visual discomfort caused by disparity.

The color temperature was adjusted in order to remove blue-light from the video. Color temperature refers to the temperature of the color that radiates from the luminous source, and it is displayed as the absolute temperature K. When the color temperature is low, the ratio of red light increases. When the color temperature is high, the ratio of blue light increases. Light is displayed as a spectrum according to its color temperature. Therefore, adjusting the color temperature can reduce the amount of blue-light. The videos were developed so that their color temperatures were 6500 K, 5500 K, 4500 K, and 3500 K. A lower color temperature means less amount of blue-light. Each video is 15 minutes long. Figure 2 shows frames from the test video.

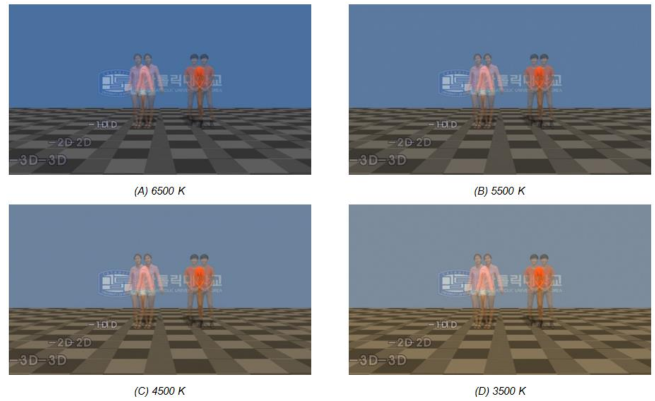

Figure 2. 3D test video

Experiment Procedure

Conventional human factor experiments have analyzed visual discomfort when watching videos through eye-blinks, saccadic movements, and surveys. However, 3D-content recognition ability is also important when watching 3D content. This study measures NPC in order to measure the changes in 3D-content recognition ability.

The experiment procedure is as follows. First, the purpose of the experiments and precautions were explained to the subjects, and they were asked to sign a consent form. After the subjects signed the consent form, their NPC was measured. Surveys were submitted to the subjects in order to determine how they felt subjectively. The surveys consist of eight questions. Q1 and Q2 are related to eyestrain and dryness. Q3 and Q4 are related to double and blurry images. Q5 and Q6 are related to dizziness and headaches. Q7 and Q8 are related to hazy and sensational feelings. Each question has 1–5 answer options, with 1 being "absolutely not" and 5 being "highly yes." After the surveys, EyeLink was set up to measure the subjects' eye movements, and the subjects were asked to watch the videos. The subjects watched a 15-minute-long video alone in a closed dark room. After the video finished, NPC was measured and the same survey was conducted. Measuring NPC after conducting the survey could give time to the eyes to recover, and thus measuring NPC was performed prior to conducting the survey. Before playing the next video, the subjects were given 10 minutes to rest their eyes because this could reduce the effects of the previous video. The same experiment procedures were conducted with the four videos developed by adjusting the blue-light. Table 1 lists the survey questions.

Table 1. Survey questions

Question 1	Do you feel eyestrain?
Question 2	Do you feel eye dryness?
Question 3	Do you see a double image?
Question 4	Do you see blurry?
Question 5	Do you have a headache?
Question 6	Do you feel dizziness?
Question 7	Do you have a hazy feeling?
Question 8	Do you have a sensational feeling in your eyes?

Eye-blink is measured to determine eye dryness, and this is linked directly to eyestrain as well. Increased eye fatigue increases

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the number of eye-blinks, and the number is counted in order to measure the level of visual discomfort. Saccadic movement is used to measure eyestrain. Increased eye fatigue decreases the number of saccadic movements. When watching a 3D image, both eyes rest on the same spot to perform vergence. NPC measures this to determine its effect on watching 3D content. The purpose of the survey is to determine how the subjects feel subjectively.

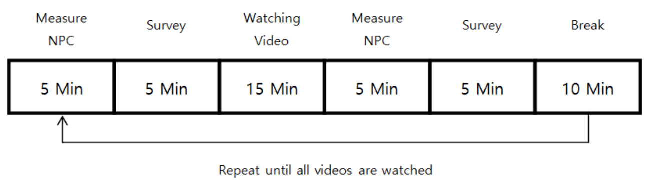

Figure 3. Test procedure

Experiment Results

The NPC measured before and after watching the videos, surveys, eye-blinks, and saccadic movements were then analyzed. Eye-blinks and saccadic movements are measured using the data recorded from EyeLink 1000 plus. EyeLink recorded eye movement while the subjects watched the videos at a rate of 1000 movements per second. Eye-blinks, saccadic movements, NPC, and changes in survey answers after watching 6500 K, 5500 K, 4500 K and 3500 K videos are analyzed.

The number of eye-blinks performed while watching each video is counted based on the data recorded by EyeLink. The number of eye-blinks per video is compared and analyzed. The more blue-light is reduced from the video, the lower is the number of eye-blinks. The number of eye-blinks is highest for the 6500 K video, and lowest for the 3500 K video. Figure 5 shows a graph with the number of eye-blinks. The y-axis represents the number of eye-blinks. Anova test results show that the p-value is lower than 0.05. The number of eye-blinks is higher when the subjects experience eye dryness. The more blue-light is reduced from the video, the lower is the number of eye-blinks. This shows that blue-light causes eye dryness, and that eliminating blue-light allows less dryness in the eyes.

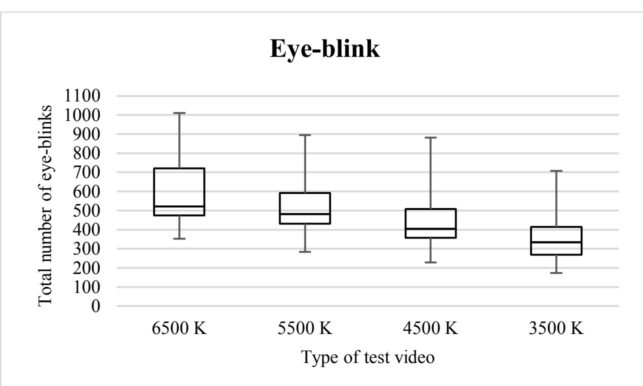

Figure 4. Eye-blink box plot

The number of saccadic movements is counted based on the data recorded by EyeLink. The number of saccadic movements performed for each video is compared and analyzed. As more blue-light is reduced from the video, the number of saccadic movements increases. The number is lowest when the color temperature of the video is 6500 K, and highest for the 3500 K video. Figure 6 shows a graph with the number of saccadic movements. The y-axis of the graph represents the number of saccadic movements. The p-value of the saccadic movement data is lower than 0.05. The lower the saccadic movement, the higher is the level of eye fatigue. Reducing the amount of blue-light reduces the level of eyestrain. This shows that blue-light causes eye fatigue and that reducing blue-light can reduce the level of eyestrain.

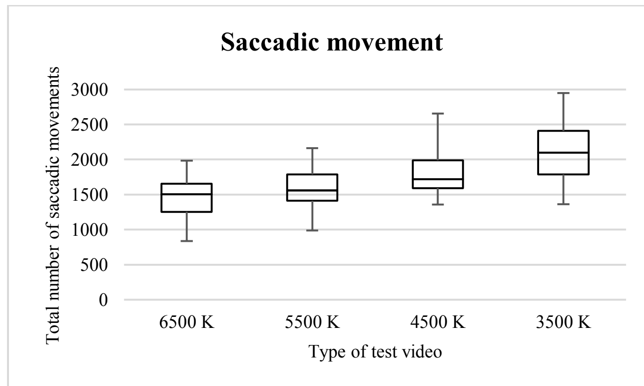

Figure 5. Saccadic movement box plot

NPC is compared before and after watching a video. A higher NPC value means that both eyes do not rest on the same spot. This becomes an obstacle when watching 3D video. The change is greatest for the 6500 K video, and as the color temperature decreases, the NPC change also decreases. The change is lowest for the 3500 K video. Reducing blue-light from the video lowers the change in NPC. Figure 7 shows a graph with NPC values. The y-axis of the graph represents cm. B is the measurement prior to watching the video, and A is the measurement after watching the video. The median values of 5500 K and 4500 K are equivalent to the upper 25%. The p-value of the NPC data is lower than 0.05. When watching 3D video, the two eyes rest on the same spot in order to conduct vergence. NPC refers to the degree at which the two eyes meet on a single spot. The lower the NPC value, the better is the ability of the eyes to meet on a single spot. In other words, a lower NPC means that one can watch 3D video better. NPC is lower in video from which blue-light is removed; a lower change in the number before and after watching the video means that blue-light has a negative effect in 3D content-recognition ability.

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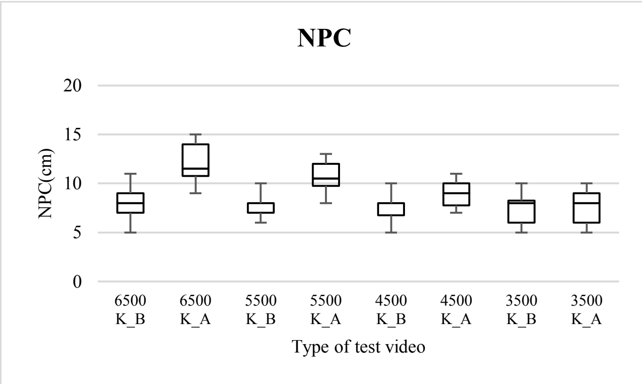

Figure 6. NPC box plot (B: Before, A: After)

The surveys conducted before and after watching a video are analyzed. We used Q1 and Q2, Q3, Q5 questions to analyze the level of eyestrain because these questions have meaningful differences between before and after watching video. For all videos, the level of eyestrain increases after watching the video. As more blue-light is reduced from a video, the level of eyestrain increases slightly after watching the video. The greatest increase occurs for the 6500 K video, and a light increase is witnessed for the 3500 K video. The subjects indicated greater eyestrain after watching the video than before watching it. In addition, the level of eyestrain is reduced when blue-light is removed. Figure 8 shows a graph with the averaged survey results regarding Q1 and Q2, Q3, Q5. The p-value of the survey data is lower than 0.05.

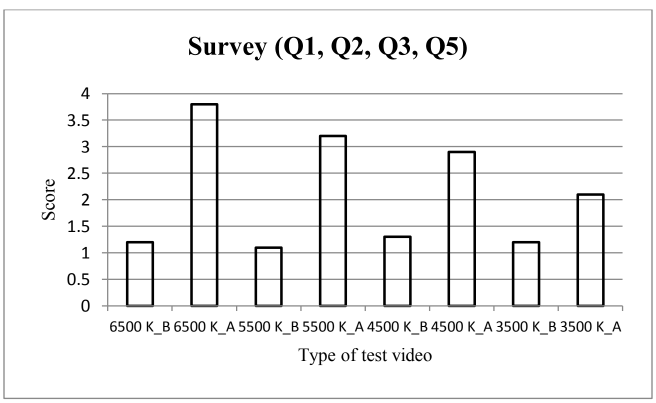

Figure 7. Survey about Q1 and Q2, Q3, Q5 (B: Before, A: After)

When blue-light is removed from a video, the number of eye-blinks and changes in NPC decrease, whereas saccadic movements increase. Blue-light causes eye dryness, and thus removing blue-light reduces the number of eye-blinks. Because blue-light causes eyestrain, removing it from videos increases saccadic movements. The surveys conducted to determine how the subjects feel subjectively show that reducing blue-light lowers the level of visual discomfort. Eye-blinks, saccadic movements, and changes in the survey answers show that blue-light causes visual discomfort, and that removing blue-light reduces the level of visual discomfort. Changes in NPC are lower after removing blue-light because subjects experience less eyestrain. Moreover, changes in NPC show that blue-light has a negative effect in 3D-content recognition ability.

Conclusion

This study analyzed the visual discomfort caused by blue-light when watching 3D video. An experiment was conducted with videos from which blue-light was removed. Eye-blinks, saccadic movements, NPC, and surveys were used to measure the level of fatigue. EyeLink 1000 plus was used to record eye movement and measure eye-blinks and saccadic movements. NPC was measured and a survey was conducted before and after watching the videos to determine how the subjects felt. The results showed that blue-light is one of the causing factors of visual discomfort, and that watching video with no blue-light causes less fatigue than video with blue-light. Moreover, it was also verified that blue-light has a negative effect on 3D-content recognition ability.

In the future, other factors that cause visual discomfort, in addition to blue-light, will be observed in order to reduce the level of fatigue in 3D content. This will be helpful in developing 3D content that causes less eyestrain to viewers and will bring the distribution of HMD forward.

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