https://doi.org/10.2352/ISSN.2470-1173.2017.14.HVEI-146

Comparison of Visual Discomfort and Visual Fatigue between Head-Mounted Display and Smartphone

Jungmin Han; KAIST; Daejeon, Korea
Seon Hee Bae; Hansol eye clinic; Daejeon, Korea
Hyeon-Jeong Suk; KAIST; Daejeon, Korea

Abstract

With the rapid development of mobile Head-Mounted Display (HMD), the problem of visual discomfort and visual fatigue caused by watching Virtual Reality (VR) contents became a crucial concern for consumers and manufacturers, especially given that the casing of mobile HMD keeps the phone at a specified distance from the lenses that is close to the eyes. In this regard, we conducted both subjective and objective measure to evaluate visual discomfort and visual fatigue caused by watching HMD and smartphones. Participants answered Simulator Sickness Questionnaire (SSQ) and went through optometric tests that measure tear break-up time, spherical equivalent, and contrast sensitivity. Experimental results show that HMD causes more eye dryness compared to smartphones.

Introduction

With the introduction of mobile Head-Mounted Display (HMD) to the public consumer market, Virtual Reality (VR) has become widely accessible in the market [1]. A number of companies jumped into mobile VR HMD business and the problem of visual discomfort and visual fatigue caused by watching VR applications became a crucial concern for consumers and manufacturers [2]. As the casing of mobile HMD keeps the phone at a specified distance from the lenses that are close to the eyes, for a successful market introduction, the issue of visual discomfort and visual fatigue should be addressed and resolved.

Within the past 10 years, research on HMD visual discomfort and visual fatigue has yielded remarkable results [3], [4]. In studies related to HMD, visual discomfort refers to a physical and/or a psychological state assessed by the users by asking the viewer to report its level of perceived annoyance [5]. Visual discomfort is reported to include headaches, eyestrain, and blurred vision [6]. A variety of techniques have been used to investigate visual discomfort, and the major tool utilized in this investigation was the Simulator Sickness Questionnaire (SSQ) [7], [8], which is still widely used by researchers. While self report checklists may have been criticized for being subject to fabrication, they have a proven record of predictive validity [9]. This widely accepted questionnaire is known to be as reliable as the objective measurements developed to replace them [10].

Visual fatigue, which is often interchangeably used with visual discomfort [4], is a symptom of a medical condition that can be measured objectively. Visual fatigue can be caused by the repetition of excessive visual efforts, which can be accumulated, and then disappears after an appropriate period of rest [4]. A number of researchers attempted to measure visual fatigue using different approaches such as eye blinking [11], EEG [12], fMRI [13], with a few notable exceptions [14].

For the purpose of the paper, we define visual fatigue as a symptom of a medical condition, which is caused by the repetition of excessive visual efforts, which can be accumulated, and disappears after an appropriate period of rest. As a subjective counterpart of visual fatigue, we use the term visual discomfort as a physical and/or a psychological state assessed by the users by asking the viewer to report its level of perceived annoyance [5, p. 186].

Whereas HMDs can increase the feeling of immersion or presence experienced by the user, its health and safety issues have been constantly raised and discussed [15]. It has been generally acknowledged that the immersive nature of HMDs creates adverse physical reactions [3], which is termed as simulator sickness [16]. It has been reported that up to 80 percent of HMD users suffer from simulator sickness [17], which includes headaches, nausea, dizziness, and eye strain caused by using HMDs. Extensive research about visual discomfort has been conducted in various fields, including computer monitor and HDTV context [18]. The research conducted by Sharples and her colleagues [19] showed that when watching VR contents using HMD, desktop, and projection display systems, HMD showed the most remarkable symptoms induced by VR. In these circumstances, researchers attempted to find out the factors that causes visual discomfort, measure the degree of annoyance, and relieve the symptoms in HMD context [3], [19]. However, from the authors' knowledge, none has compared the visual discomfort and fatigue between HMD and smartphone. Furthermore, previous research on visual discomfort has mostly relied on subjective assessment methods [7], which inevitably raised the issue of ambiguity. While subjective human factors are also important in analyzing visual discomfort, objective assessment methods for the evaluation is needed to observe physiological change [4].

Citation of prior art are better here but additional review of other methods (e.g. Banks et al) and visual discomfort generally (i.e. A Wilkins) would improve the paper.

In this regard, this study intends to measure visual discomfort and visual fatigue of HMD and smartphone and compare them. By doing so, we attempt to show consumers how visual discomfort and visual fatigue caused by HMD is comparable to conventional smartphone standards. The subsequent section will describe our preliminary experiment conducted before the main experiment.

Preliminary Experiment

We planned a preliminary experiment before delving into the main experiment to investigate visual discomfort and visual fatigue caused by HMD. The experiment was conducted at the ophthalmic clinic in Daejeon, Korea, with 6 participants (4 males and 2 females, age from 23 to 39). We used two different mobile phones with LCD and AMOLED display respectively, LG G5 and Samsung Galaxy S7. They represent one dominant mobile category in the current consumer market. As the Galaxy S7 has AMOLED panel, it was perceived to be brighter than LG G5 with the same luminance; however, the experiment was conducted with both mobiles having the same luminance. As for a mobile VR HMD, we used BaofengMojing 3, which is certified to work with any Android smartphones with screen sizes measuring from 4.7 inches to 6.0 inches. All participants were confirmed to have neither strabismus nor color deficiency.

Metrics and Stimuli

Optometric tests

As for physiological measurements of visual fatigue, we conducted three optometric tests, which are tear break-up time (BUT), spherical equivalent for near vision, and contrast sensitivity. We selected these three measurements because it is well known that HMD users often complain about annoyance of eye-dryness, temporal myopia, and blurred vision. BUT was measured to assess dryness of eyes. People with dry eyes have unstable tear film that breaks up faster. The spherical equivalent is the average of the dioptric powers in all meridians of a lens, which shows myopic shift or accommodation for near vision. Lastly, contrast sensitivity refers to a measure of the ability to discern static image in situations of different luminance levels and we used Functional Acuity Contrast Test (FACT) to measure it. We used the following ophthalmic instruments for the experiment: slit lamp BP900 from Haag-Streit International to measure BUT, Topcon KR-8800 (Auto Kerato-Refractometer) to measure spherical equivalent for near vision, and OPTEC6500 (vision tester/glare remote control) from Stereo Optical Company for contrast sensitivity. Figure 2 shows the execution of aforementioned tests. The result of each test will show how user's eyes change after watching HMD during the experiment. It is important to note that, because the change of eye condition is temporal and shows rapid deterioration in few seconds, HMD was removed in front of the ophthalmologist just before the test in order to minimize the possible deterioration. On average, tests began within 1 second after removing the HMD.

FIGURE 1 OPTOMETRIC TESTS

SSQ

We used SSQ for psychological measurement of visual discomfort. SSQ is one of the most widely used questionnaire to measure a user's perceived annoyance [7]. SSQ is constituted with 3 clusters of symptoms: Oculomotor disturbances (O) Disorientation (D), and Nausea (N). Scores on the Nausea (N) subscale are based on the report of symptoms that relate to gastrointestinal distress such as nausea, stomach awareness, salivation, and burping. Scores on the Oculomotor disturbances (O) subscale relate to eyestrain, difficulty in focusing, blurred vision, and headache. Scores on the Disorientation (D) subscale are about vestibular disturbances such as dizziness and vertigo. All items had to be assessed on a scale labeled with the adjective terms [never]-[seldom]-[occasionally]-[often], which were transformed into numerical values ranging from 0 to 3. A weighted average of these three factors comprises the total score, which reflect the severity of the symptomatology for an individual and can be used to measure simulator sickness. The level of the symptoms would be useful for signaling the seriousness of the visual discomfort. As the purpose of this study is to compare the visual discomfort of two different displays, we compared each categories (N,D,O) to focus on what features should be reported.

Three materials were used for the experiment to collect data regarding visual fatigue and visual discomfort: BBC Click 360, Korea 360 Gangnam, and Korea 360 Boseong market. As optometric tests had to be conducted directly after the HMD experience to collect precise measurements, we prepared three materials to conduct three tests explained above respectively. Participants filled in the SSQ after each viewing.

Procedure

When entering the experimental room, participants were firstly briefed about their task. Participants were provided with an informed consent form containing information about the screening and the experiment, and about the possible occurrence of visual discomfort and visual fatigue. After signing the informed consent, participants performed a short training to familiarize with the experiment and the tests they will go through. Once the introduction was complete, prior to the experiment, an extensive optometric screening was carried out on the participants. The screening was performed to confirm that no participant has eye disease or severe binocular abnormalities (e.g., strabismus) and to familiarize participants with the optometric tests.

All experiments were performed in a controlled lab experiment and took approximately 130 minutes. Instructors told participants that they can give up the viewing if they feel extreme sickness and do not want to proceed the experiment. Participants were randomly allocated to use Samsung Galaxy S7 or LG G5. Prepared visual materials were played on the mobile phones using BaofengMojing 3, with constant luminance at approximately 460nit. Each video clip was 20 minutes length and participants went through one optometric test immediately after removing the HMD because the symptoms are temporal and may recover in few minutes. For this reason, participants watched three contents using HMD to measure BUT, spherical equivalent for near vision, and contrast sensitivity. After the tests, the SSQ was administered and participants took 15 minutes break to rest eyes. Participants were not allowed to use smartphones or watch visual materials during the break time. They were guided to close their eyes and relax. When participants finished their viewings, a researcher conducted semi-structured interview about their experience with HMD and smartphone viewing in relation to perceived psychological and physiological change. Participants were asked to describe their feelings and visual discomfort.

Results and Discussions

Whereas the participants did not complain of dry eyes, there was a significant decrease of BUT for all participants, on average 3 seconds decrease for both eyes. Whereas researchers instructed them not to rest their eyes during the HMD viewing, one participant remarked from the interview that he blinked more than usual to prevent eye dryness. However, the value of his BUT has significantly decreased as well. While the decrease of BUT was evident, individual change of spherical equivalent value varied and showed clear personal differences. The value of spherical equivalent changed from -0.50 to +0.25. Interestingly, 3 users showed increased spherical equivalent value, which calls for a further investigation with more samples. Contrast sensitivity, which is the visual ability to see objects that may not be outlined clearly or that do not stand out from their background, stayed in normal range and did not show significant change after watching the materials. The result of SSQ showed that the users suffered from visual discomfort as expected [8]. Because of the limited number of samples, data were not statistically analyzed but guided us to design the main experiment. During the preliminary experiment, we realized that BUT and spherical equivalent can be measured in a row.

Experiment

We conducted main experiment to compare visual discomfort and visual fatigue caused by HMD and smartphone. The experiment was conducted at the ophthalmic clinic in Daejeon, Korea, with 24 participants (15 males and 9 females, age from 18 to 27). Same as the preliminary experiment, all participants were confirmed to have neither strabismus nor color deficiency. Apple iPhone 6S and Samsung Galaxy S7 were used for the experiment. As the Galaxy S7 has AMOLED panel, it appears to be brighter than iPhone 6S with the same luminance; however, the experiment was conducted with both mobiles having the same luminance of 462nit. Mobile phones were mounted on BaofengMojing 3 for HMD experience.

Procedure, Metrics and Stimuli

We generated materials for HMD viewing using LG 360 cam. The first one is daytime campus driving and the second is nighttime campus bicycling [Figure 3]. Each video clip was 20 minutes length and participants went through the tests directly after removing a HMD. Optometric test had to be conducted directly after watching the HMD because the symptoms are temporal and soon recovered. For this reason, participants watched two contents for HMD and smartphone. BUT and spherical equivalent were measured after the first clip and contrast sensitivity was measured after the second clip. After the screening, participants filled in a SSQ and took 15 minutes break to rest eyes. Participants were not allowed to use smartphones or watch visual materials during the break time. Participants were told to close their eyes and relax. Other procedures are the same as those of the preliminary experiment.

Regarding the experiment with smartphone, all participants watched the smartphone screen at a distance of 40cm away to simulate a normal smartphone using environment. In this experiment, we showed two nature documentaries about land and sea, 20 minutes each. Other procedures are identical to the HMD experiment. When participants finished their viewings, a researcher conducted semi-structured interview about their experience with HMD and smartphone viewing.

FIGURE 2 STIMULI FOR HMD AND SMARTPHONE VIEWING

Results and Discussions

SSQ

As we have mentioned in the previous section, participants watched four materials in total and completed SSQ after each session. Consequently, we collected five SSQ completed by one user; before the experiment, after watching two contents on HMD, and after watching two contents on smartphone. The contents used for HMD and smartphone are similar yet not identical. However, the result of paired samples t-test proved that the difference of SSQ score between the two contents used for each device is not statistically significant in three categories: nausea (N), oculomotor disturbances (O), and disorientation (D) [Table 1]. For instance, there was no statistically significant difference between the score of nausea of two different HMD contents; daytime driving and nighttime bicycling. The result of paired samples t-test was t(23)=-1.18, which also shows p=0.25 (two-tailed test), which is higher than the significance level of 0.05.

TABLE 1 PAIRED SAMPLES TEST

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	SSQ_n_D SSQ_n_N	.11	.45	.09	-.30	.08	-1.18	23	.25
Pair 2	SSQ_o_D SSQ_o_N	.07	.36	.07	-.22	.08	-.97	23	.34
Pair 3	SSQ_d_D SSQ_d_N	.60	.30	.06	-.19	.07	-.97	23	.34
Pair 4	SSQ_n_E SSQ_n_W	.65	.17	.04	-.14	.01	-1.85	23	.08
Pair 5	SSQ_o_E SSQ_o_W	.12	.29	.06	-.24	.00	-2.00	23	.06
Pair 6	SSQ_d_E SSQ_d_W	.05	.17	.03	-.12	.02	-1.57	23	.13

Therefore, we adopted an average score of two SSQ scores for further analysis. Finally, the analysis included three conditions: before experiment, after watching HMD, and after watching smartphone, in three categories: nausea (N), oculomotor disturbances (O), and disorientation (D). Then, we conducted repeated measure one-way ANOVA of three categories (N, O, D) in three different conditions, which is followed by Bonferroni post-hoc test to statistically analyze the pairwise mean difference. As a result, the score of each category increased in a statistically meaningful level after the experiment at an alpha level of 0.05. The scores also increased in the case of smartphone, however, there was no statistically significant difference [Table 2].

TABLE 2 DESCRIPTIVE STATISTICS

	N	Mean	Std. Deviation
SSQ_n_base	24	.14	.19
SSQ_o_base	24	.45	.40
SSQ_d_base	24	.17	.24
SSQ_n_HMD	24	.66	.54
SSQ_o_HMD	24	1.10	.67
SSQ_d_HMD	24	.74	.76
SSQ_n_Smart	24	.18	.21
SSQ_o_Smart	24	.61	.43
SSQ_d_Smart	24	.24	.29
Valid N (listwise)	24		

This confirms that watching a HMD causes more visual discomfort compared to watching a smartphone, which is in line with Pölönen and her colleagues' research [20]. The following figures show how nausea, oculomotor disturbance, and disorientation change after using HMD and smartphone.

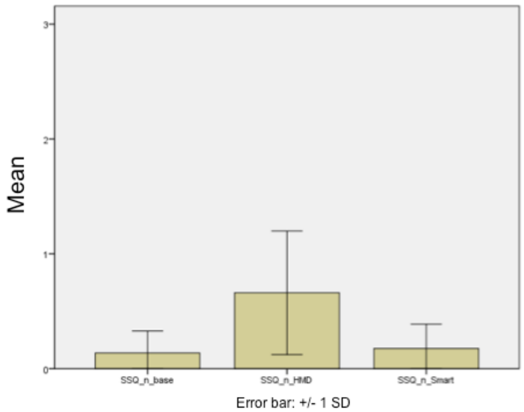

Figure 3 Nausea before the viewing, after HMD viewing, and after smartphone viewing

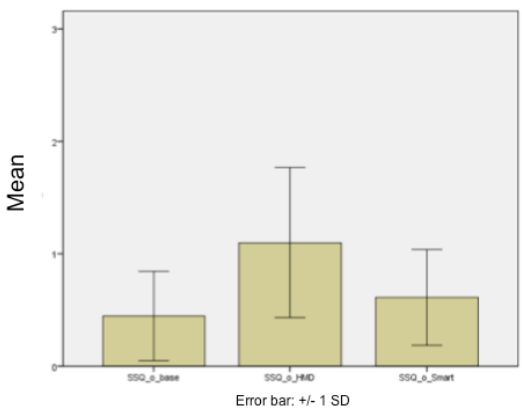

Figure 4 Oculomotor disturbances before the viewing, after HMD viewing, and after smartphone viewing

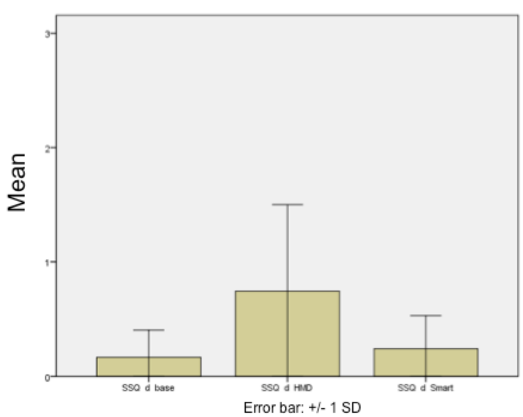

Figure 5 Disorientation before the viewing, after HMD viewing, and after smartphone viewing

Optometric tests

We performed within group one-way ANOVA with BUT data collected before the experiment, after watching HMD, and after watching smartphone. As a result, the change of mean value was statistically significant for both left and right eyes [Left $F(2,46)=46.19$, $p < 0.01$, Right $F(2,46)=19.57$, $p< 0.01$]. Post-hoc test showed that this is because both eyes had significant BUT change after watching HMD. The BUT after watching HMD has significantly decreased compared to the time before the experiment or after watching smartphone. BUT has also decreased after watching smartphone, however, is not statistically significant at an alpha level of 0.05. Figure 6 shows BUT of left and right eyes: before the experiment, after HMD viewing, and after smartphone viewing.

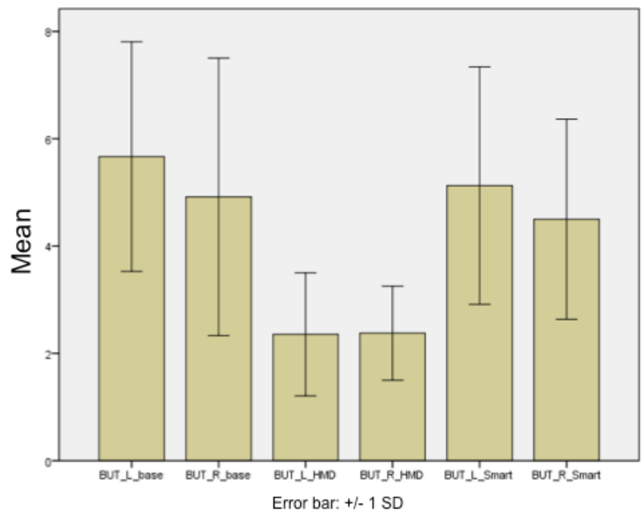

Figure 6 BUT of left and right eyes before the viewing, after HMD viewing and after smartphone viewing

The value of spherical equivalent of both eyes decreased after watching HMD and smartphone; on average, left eye from -3.06 to -3.39 and -3.39, right eye from -3.10 to -3.25 and -3.27. We performed within group one-way ANOVA for each changes, which showed statistically significant change of spherical equivalent of left eye [$F(2, 46) = 8.08$, $p < 0.01$] but not in case of right eye [$F(2, 46) = 2.68$, $p = 0.08$]. Post-hoc test result proved that regardless of the significant change of spherical equivalent of left eye after watching HMD and smartphone, the influence of HMD and smartphone viewing was not statistically significant. It is interesting to note that the mean value of spherical equivalent after watching each display appeared to be identical up to the second digit after the decimal point. In case of right eye, only after watching smartphone, spherical equivalent decreased in a meaningful level. This means that whereas participants did not notice a loss of their visual capability, the participants had myopic shift or accommodation. However, different from the significant decrease of BUT after HMD viewing, the change of spherical equivalent was not significantly different between HMD and smartphone.

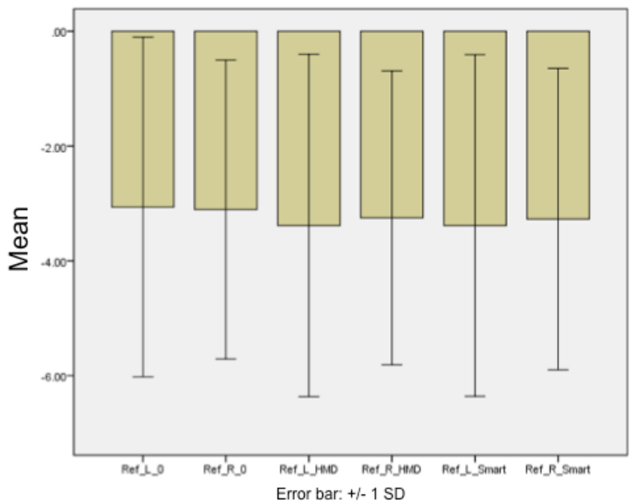

FIGURE 7 SE BEFORE THE VIEWING, AFTER HMD VIEWING AND AFTER SMARTPHONE VIEWING

The result of contrast sensitivity showed that a participant's contrast sensitivity stayed in normal range and did not show significant change after watching the materials on HMD and smartphone, which was expected from the preliminary experiment.

General Discussions

The aim of this study was to compare the visual fatigue and visual discomfort between HMD and smartphone usage. The initial experiment showed that watching HMD and smartphone both caused myopic shift, while participants could not notice this loss of visual capability. This mild myopic shift or accommodation is a temporary condition that can be recovered in few minutes. Furthermore, it is important to note that participants did not show more myopic shift compared to that of smartphone, which contradicts the general belief that using HMD will harm eye vision more than smartphones.

In addition, regarding BUT experiment, it has been revealed that HMD viewing causes drier eyes and result in increased visual discomfort compared to smartphone viewing. A subsequent experiment confirmed the result of preliminary experiment, proving that HMD causes more eye dryness compared to smartphone. This eye dryness can be recovered in a minute and it is known that having drier eyes for a short period of time does not influence the functioning of eyes in general. However, it should be recommended to use eye drops before and after watching HMD to relieve this temporal eye dryness. Also, watching HMD for a long period of time, for instance, longer than 30 minutes, may cause even drier eyes. Therefore, it also should be recommended to users not to use HMD for more than 30 minutes, as is already noted by manufacturers.

Whereas many people report visual complaints when watching HMD, previous research revealed a lack of consensus in indicators to evaluate these visual complaints. We performed an experiment and measured BUT, spherical equivalent for near vision, and contrast sensitivity to measure objective signs of visual fatigue and subjective symptoms of visual discomfort. The result reveals that not all clinical tests are equally appropriate to evaluate the visual fatigue caused by HMD viewing. In addition, there is a natural variation in susceptibility to visual complaints among people with normal vision.

In our experiment, 24 participants performed three optometric tests and one questionnaire before and after watching HMD and smartphone for 20 minutes. Our results show that HMD viewing did show clinically meaningful changes. Participants showed significantly shorter BUT and decreased spherical equivalent after watching HMD compared to those after smartphone viewing. Moreover, whereas the changes of spherical equivalent and contrast sensitivity of HMD and smartphone viewing did not show much statistically meaningful difference, the difference of BUT was significant. The cause of this significant change of BUT is still in a black box, which calls for a further study. One possible explication of this eye dryness can be the lack of eye blinking. Even though a number of participants mentioned from the interviews that they tried to blink their eyes in order not to have dry eyes, the change was drastic. It should also be noted that the detection of visual fatigue with optometric indicators was complicated since the changes have a rapid deterioration. This rapid deterioration may have been the reason why Peli (1998) did not reveal any clinically meaningful visual fatigue, because he performed all his tests as a set before and after a stimulus [21].

Lastly, we would like to mention that different content or length of stimuli could show more statistically meaningful results. Longer or more stressful stimuli could be used for the experiment that will have more profound impact on the visual system and show interesting results. However, this may raise ethical issues since long-term visual complaints, nauseousness, and headaches might be induced. In reality, because of personal difference of susceptibility, a few participants suffered from nausea and headache after the experiment. If more contents are developed that users can enjoy with AMOLED display, with proper break time, users will be able to immerse themselves without much concern on damaging their vision.

Conclusions

This paper has described a controlled study of the visual discomfort and visual fatigue experienced by participants in different types of displays, HMD and smartphone. The data indicates that the main situation in which symptoms are induced is for HMD use. Effects are also experienced in smartphone, although the level of effect was not statistically significant. Although these results indicate that there is no proof for widespread concern that HMD may cause serious visual fatigue, for some individuals there was a definite experience of severe negative effects. For instance, two participants confessed that they suffered from serious headache for a whole day after the experiment. One participant indicated that her nauseousness lasted even until the next day. Therefore, it is important to find solutions to mitigate such symptoms of visual discomfort. Even though our results imply that HMD did not cause serious visual fatigue, we should note the eye dryness that can be caused by HMD because of possible loss it may bring about, such as decreased work productivity [22], impaired functional visual acuity, and increased risk of eye infection. In this regard, we suggest that longitudinal study will be needed to track the change of visual acuity with the use of HMD.

HMD and VR are still in their development phase, and there is a need to continue research into monitoring the types and levels of symptoms experienced by users as this new system develops.

Some HMD users are still experiencing symptoms to an uncomfortable and distressing level, which calls for a research to identify the causes of these symptoms. However, it is also desirable to identify how the symptom levels can be mitigated for those people who are particularly sensitive to visual discomfort. This can be done by conducting additional experiments with different types of contents and displays.

References

[1] C. Anthes, M. Wiedemann, and D. Kranzlmüller, "State of the Art of Virtual Reality Technology," 2016, no. March.

[2] D. Magyari, "Virtual Reality: Are Health Risks Being Ignored?," *CNBC*, 2016. [Online]. Available: http://www.cnbc.com/2016/01/08/virtual-reality-are-health-risks-being-ignored-commentary.html. [Accessed: 01-Aug-2016].

[3] K. Carnegie and T. Rhee, "Reducing Visual Discomfort with HMDs Using Dynamic Depth of Field," *IEEE Computer Graphics and Applications*, vol. 35, no. 5. pp. 34–41, 2015.

[4] M. Lambooij, W. IJsselsteijn, M. Fortuin, and I. Heynderickx, "Visual Discomfort and Visual Fatigue of Stereoscopic Displays: A Review," *J. Imaging Sci. Technol.*, vol. 53, no. 3, pp. 030201–1, 2009.

[5] J. Li, M. Barkowsky, and P. Le Callet, *Visual Discomfort in 3DTV: Definitions, Causes, Measurement, and Modeling. In Novel 3D Media Technologies*. Springer New York, 2015.

[6] J. E. Sheedy, J. Hayes, and J. Engle, "Is All Asthenopia the Same?," *Optom. Vis. Sci.*, vol. 80, no. 11, pp. 732–739, 2003.

[7] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," *The International Journal of Aviation Psychology*, vol. 3. pp. 203–220, 1993.

[8] R. S. Kennedy, J. Drexler, and R. C. Kennedy, "Research in Visually Induced Motion Sickness," *Appl. Ergon.*, vol. 41, no. 4, pp. 494–503, 2010.

[9] S. F. Wiker, R. S. Kennedy, M. E. McCauley, and R. L. Pepper, "Susceptibility to seasickness: Influence of hull design and steaming direction," *Aviat. Space. Environ. Med.*, vol. 50, no. 10, pp. 1046–1051, 1979.

[10] R. S. Kennedy, J. M. Drexler, D. E. Compton, K. M. Stanney, D. Susan Lanham, and D. L. Harm, "Configural Scoring of Simulator Sickness, Cybersickness and Space Adaptation Syndrome: Similarities and Differences?," *Virtual Adapt. Environ. Appl. Implic. Hum. Perform. issues*, vol. 247, 2003.

[11] M. Rosenfield, "Computer Vision Syndrome: A Review of Ocular Causes and Potential Treatments," *Ophthalmic Physiol. Opt.*, vol. 31, no. 5, pp. 502–515, 2011.

[12] Y. J. Kim and E. C. Lee, "EEG based Comparative Measurement of Visual Fatigue Caused by 2D and 3D Displays," *Commun. Comput. Inf. Sci.*, vol. 174 CCIS, no. PART 2, pp. 289–292, 2011.

[13] C. Chen, J. Wang, K. Li, Y. Liu, and X. Chen, "Visual Fatigue Caused by Watching 3DTV: an fMRI Study," *Biomed. Eng. Online*, vol. 14, no. Suppl 1, p. S12, 2015.

[14] M. Lambooij, M. Fortuin, W. IJsselsteijn, and I. Heynderickx, "Measuring visual discomfort associated with 3D displays," *J. Soc. Inf. Disp.*, vol. 18, no. 11, pp. 931–943, 2010.

[15] H. Takada and M. Miyao, "Visual Fatigue and Motion Sickness Induced by 3D Video Clip," *Forma*, vol. 27, pp. S67–S76, 2012.

[16] M. McCauley, *Research Issues in Simulator Sickness: Proceedings of a Workshop*. National Academy Press, 1984.

[17] K. M. Stanney, K. S. Hale, I. Nahmens, and R. S. Kennedy, "What to Expect From Immersive Virtual Environment Exposure: Influences of Gender, Body Mass Index, and Past Experience," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 45, no. 3, pp. 504–520, 2003.

[18] S. Yano, S. Ide, T. Mitsuhashi, and H. Thwaites, "A Study of Visual Fatigue and Visual Comfort for 3D HDTV / HDTV Images," *Displays*, vol. 23, pp. 191–201, 2002.

[19] S. Sharples, S. Cobb, A. Moody, and J. R. Wilson, "Virtual Reality Induced Symptoms and Effects (VRISE): Comparison of Head Mounted Display (HMD), Desktop and Projection Display Systems," *Displays*, vol. 29, no. 2, pp. 58–69, 2008.

[20] M. Pölönen, T. Järvenpää, and J. Häkkinen, "Reading E-books on a Near-to-eye Display: Comparison between a Small-sized Multimedia Display and a Hard Copy," *J. Chem. Inf. Model.*, vol. 33, no. 3, pp. 157–167, 2012.

[21] E. Peli, "The Visual Effects of Head-mounted Display (HMD) Are Not Distinguishable From Those of Desktop Computer Display," *Vision Res.*, vol. 38, no. 13, pp. 2053–2066, 1998.

[22] M. Yamada, Y. Mizuno, and C. Shigeyasu, "Impact of Dry Eye on Work Productivity," *Clin. Outcomes Res.*, vol. 4, no. 1, pp. 307–312, 2012.

Author Biography

Jungmin Han received her PhD at Manchester Business School in the UK. Before this, she obtained her MS in design management and BS in industrial design at KAIST, Daejeon, Korea. Currently, she is working as a lecturer at KAIST in industrial design department.

Seon Hee Bae received her PhD in medicine at Konyang University after finishing her MD at Chungnam national university. She is specialized in retina and her research interest lies on macular disease. She is now the director of Hansol eye clinic in Daejeon, Korea.

Hyeon-Jeong Suk received her BS and MS degrees in industrial design from KAIST, Republic of Korea, and her PhD degree in psychology from the University of Mannheim, Germany. Currently, she is an associate professor of KAIST leading a color laboratory. Her research interests include color psychology and emotional design.