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Visual Discomfort and Visual Fatigue: Comparing Head-Mounted Display and Smartphones

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Objective: This study aims to evaluate visual discomfort and visual fatigue caused by watching HMD and smartphones by conducting both subjective and objective measure.

Background: 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.

Method: Two smartphones were chosen for a preliminary study: LG G5 and Galaxy S7. As for a main study, iPhone 6S and Galaxy S7 were used. After being exposed to the selected clips, participants were asked to answer Simulator Sickness Questionnaire (SSQ) and went through optometric tests that measure tear break-up time, spherical equivalent, and contrast sensitivity.

Results: The subjective assessments indicate that HMD causes more visual discomfort compared to watching a smartphone. Furthermore, the experimental result confirms that watching a HMD causes more eye dryness compared to smartphones.

Conclusion: The result of the study compared visual discomfort and visual fatigue of two different displays, HMD and smartphone, and confirmed that watching HMD causes more visual discomfort and visual fatigue.

Application: Ultimately, this study could help manufacturers understand the strengths and weaknesses of different display forms, providing guidance for an effective application of HMD.

Keywords: Head-mounted display, Smartphone, Visual fatigue, Visual discomfort, Eye dryness

1. 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 (Anthes et al., 2016). 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 (Magyari, 2016). 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 (Carnegie and Rhee, 2015; Lambooij et al., 2009). 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 (Li et al., 2015). Visual discomfort is reported to include headaches, eyestrain, and blurred vision (Sheedy et al., 2003). 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) (Kennedy et al., 2010; Kennedy et al., 1993), 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 (Wiker et al., 1979). This widely accepted questionnaire is known to be as reliable as the objective measurements developed to replace them (Kennedy et al., 2003).

Visual fatigue, which is often interchangeably used with visual discomfort (Lambooij et al., 2009), 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 (Lambooij et al., 2009). A number of researchers attempted to measure visual fatigue using different approaches such as eye blinking (Rosenfield, 2011), EEG (Kim and Lee, 2011), fMRI (Chen et al., 2015), with a few notable exceptions (Lambooij et al., 2010). 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 (Li et al., 2015, p. 18).

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 (Takada and Miyao, 2012). It has been generally acknowledged that the immersive nature of HMDs creates adverse physical reactions (Carnegie and Rhee, 2015), which is termed as simulator sickness (McCauley, 1984). It has been reported that up to 80 percent of HMD users suffer from simulator sickness (Stanney et al., 2003), 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 (Yano et al., 2002). The research conducted by Sharples and her colleagues (2008) 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 (Carnegie and Rhee, 2015; Sharples et al., 2008). 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 (Kennedy et al., 1993), 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 (Lambooij et al., 2009).

In this regard, based on our previous study (Han et al., 2017), 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.

2. 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 size measuring from 4.7 inches to 6.0 inches. All participants were confirmed to have neither strabismus nor color deficiency.

2.1 Metrics and stimuli

2.1.1 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 1 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, the tests began within 1 second after removing the HMD.

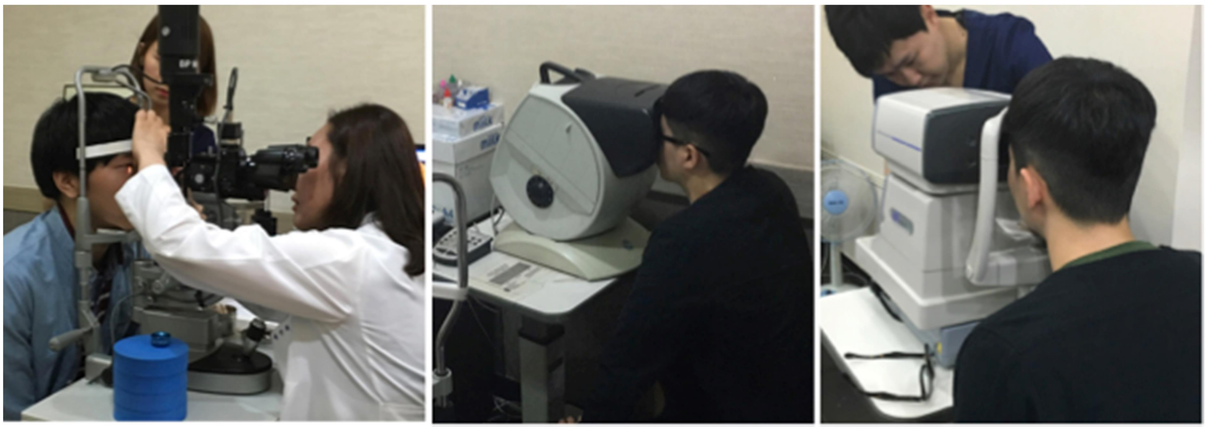

Figure 1. Optometric tests: (From left) measuring tear break-up time, contrast sensitivity, and spherical equivalent

2.1.2 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 (Kennedy et al., 1993). SSQ is constituted with 3 clusters of symptoms: oculomotor disturbances, disorientation, and nausea. Scores on the nausea 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 subscale relate to eyestrain, difficulty in focusing, blurred vision, and headache. Scores on the disorientation 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 (nausea, oculomotor disturbances, disorientation) 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.

2.2 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.

2.3 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. 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. The result of SSQ showed that the users suffered from visual discomfort as expected (Kennedy et al., 2010). 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 contrast sensitivity does not show meaningful change after watching HMD and smartphone and decided to exclude this test for the main experiment.

3. 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.

3.1 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 2). 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 was measured after the first clip and spherical equivalent 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: (Left) Campus tour at day and night (Right) BBC documentary about water and earth

3.2 Results and discussions

3.2.1 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.

Table 1. Mean comparison between the two equivalent stimuli (stimuli sets presented in Figure 2). The paired samples test yielded no statistically significant difference of the SSQ scores. (N = 24)

SSQ criteria	Stimuli for watching VR using HMD 	Stimuli for watching the smartphone 
Nausea	$t(23) = -1.18$, $p = 0.25$	$t(23) = -1.85$, $p = 0.08$
Oculomotor disturbance	$t(23) = -0.97$, $p = 0.34$	$t(23) = -2.00$, $p = 0.06$
Disorientation	$t(23) = -0.97$, $p = 0.34$	$t(23) = -1.57$, $p = 0.13$

Table 2 shows how nausea, oculomotor disturbance, and disorientation change after using HMD and smartphone and whether the difference is statistically significant. Overall, we could observe the increase of SSQ score after watching the contents. However, whereas SSQ score increased at a statistically significant level after VR viewing using HMD, it was not statistically significant after smartphone viewing.

Table 2. Mean scores of the SSQ in Nausea, Oculomotor disturbance, and Disorientation aspects. The VR and Smartphone viewings were proceeded randomly. Ratings between 0 and 3 and the Standard Deviation scores in the parentheses. (N = 24)

SSQ criteria	Baseline, before the viewing	After viewing the media contents using	
		VR in HMD	Smartphone
Nausea	0.14 (0.19)	0.66 (0.54) The increase of 0.52 is significant, Paired samples *t*-test [$t(23) = -4.86$, $p < 0.01$]	0.18 (0.21) The increase of 0.04 is not significant, Paired samples *t*-test [$t(23) = -0.94$, $p = 0.34$]
Oculomotor disturbance	0.47 (0.40)	1.10 (0.70) The increase of 0.63 is significant, Paired samples *t*-test [$t(23) = -4.09$, $p < 0.01$]	0.61 (0.43) The increase of 0.14 is not significant, Paired samples *t*-test [$t(23) = -2.11$, $p = 0.05$]
Disorientation	0.17 (0.24)	0.74 (0.76) The increase of 0.57 is significant, Paired samples *t*-test [$t(23) = -3.99$, $p < 0.01$]	0.24 (0.29) The increase of 0.04 is not significant, Paired samples *t*-test [$t(23) = -1.58$, $p = 0.13$]

This confirms that watching a VR using HMD causes more visual discomfort compared to watching a smartphone, which is in line with Pölönen and her colleagues' research (Pölönen et al., 2012). The result of SSQ shows that visual discomfort increased after watching a VR using HMD for 20 minutes, which is remarkably higher compared to that of smartphone. After watching smartphone for 20 minutes, SSQ score has slightly increased but the difference is not statistically significant.

3.2.2 Optometric tests

BUT (Tear Break-Up Time) test

With regard to the BUT measurements, some decreases were found after watching both HMD and smartphone, which indicated that the subjects' eyes became drier after watching the devices. In particular, the decrease was more drastic after watching the HMD than the smartphone. We performed paired-samples *t*-test to examine whether the decreased BUT values were statistically significant or not. As presented in Table 3, the decreased BUT values were statistically significant after watching the HMD, whereas they were not after watching smartphone at an alpha level of 0.05. The tendency was consistent for both eyes.

Table 3. Mean values of the BUT (Tear break-up time) of both eyes, measured before the experiment as the baseline and after watching the media including HMD and smartphone. The media exposure was in random order. Measured data are in second, and the Standard Deviation values in the parentheses. (N = 24)

BUT (Tear break-up time)	Baseline, before the viewing	After viewing the media contents using	
		VR in HMD	Smartphone
Left eye	5.67 (2.14)	2.35 (1.15) A decrease of 3.31 is significant, Paired samples *t*-test [$t(23) = 8.35$, $p < 0.01$]	5.13 (2.21) A decrease of 0.54 is not significant, Paired samples *t*-test [$t(23) = 1.36$, $p = 0.19$]
Right eye	4.92 (2.56)	2.38 (0.88) A decrease of 2.54 is significant, Paired samples *t*-test [$t(23) = 5.64$, $p < 0.01$]	4.50 (1.87) A decrease of 0.42 is not significant, Paired samples *t*-test [$t(23) = 0.83$, $p = 0.41$]

SE (Spherical Equivalent) test

The value of spherical equivalent of both eyes decreased after watching HMD and smartphone. We performed paired-samples *t*-test to test the statistical meaning of the decreased values. Except for the right eye of watching HMD, the decreased SE values were found to be statistically significant at an alpha level of 0.05. In line with Park and her colleagues' work, (Park et al., 2014), we could also observe that near work with smartphone could induce the change of accommodative function.

It is interesting to note that the decrease of SE after HMD viewing and smartphone viewing were not statistically significant. For instance, mean value of SE of right eye after HMD viewing and smartphone viewing were -3.25 and -3.27 respectively, which indicates no statistical difference between their mean values [$t(23) = 0.24$, $p = 0.81$]. As is shown in Table 4, mean SE after HMD viewing (-3.25) does not show statistically significant decrease compared to the mean SE before viewing (-3.10), which also does not show much difference when compared to mean SE after smartphone viewing (-3.27).

Therefore, we conclude that after watching HMD or smartphone for 20 minutes, SE decreases in a similar level, and the difference between each display has not been observed. However, it is important to note that SE decrease was not always statistically significant, which calls for a further study with more subject. Especially, given that SE is closely related to eyesight, the change of SE should be investigated further.

Table 4. Mean values of the SE (Spherical equivalent) test of both eyes, measured before the experiment as the baseline and after watching the media including HMD and smartphone. The media exposure was in random order. Measured data are in diopters and the Standard Deviation values in the parentheses. (N = 24)

SE (Spherical equivalent)	Baseline, before the viewing	After viewing the media contents using	
		VR in HMD	Smartphone
Left eye	-3.06 (2.96)	-3.39 (2.98: rounded from 2.983) A decrease of 0.32 is significant, Paired samples *t*-test [$t(23) = 3.33$, $p < 0.01$]	-3.39 (2.98: rounded from 2.977) A decrease of 0.32 is significant, Paired samples *t*-test [$t(23) = 4.74$, $p < 0.01$]
Right eye	-3.10 (2.60)	-3.25 (2.56) A decrease of 0.15 is not significant, Paired samples *t*-test [$t(23) = 1.69$, $p = 0.11$]	-3.27 (2.62) A decrease of 0.17 is significant, Paired samples *t*-test [$t(23) = 2.80$, $p = 0.01$]

4. 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 and spherical equivalent for near vision 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 spherical equivalent change 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 (Peli, 1998).

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.

5. 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 (Yamada et al., 2012), 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.

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