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## Impact of virtual reality headset use on eye blinking and lipid layer thickness

V. Marshev, J. Bolloc'h, N. Pallamin, J.-L. de Bougrenet de La Tocnaye, B. Cochener, Vincent Nourrit

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Title: Impact of virtual reality headset use on eye blinking and lipid layer thickness

Titre: Impact de casque réalité virtuelle sur clignement des yeux et couche lipidique

Short title: Impact of virtual reality headset use on eye blinking and lipid layer thickness

Titre court : Impact de casque réalité virtuelle sur clignement des yeux et couche lipidique

Author's names and degrees:

Vasilii Marshev<sup>1,2,3</sup>, MsC

Johanne Bolloc'h<sup>1,2</sup>, BsC

Nico Pallamin<sup>4</sup>, BsC

Jean-Louis de Bougrenet de la Tocnaye<sup>1,2</sup>, PhD

Beatrice Cochener<sup>5</sup>, PhD

Vincent Nourrit<sup>1,2</sup>, PhD

1 - Optics department, IMT Atlantique Bretagne-Pays de la Loire, Campus de Brest,  
Technopôle Brest-Iroise, CS 83818, 29238 Brest, Cedex 03, France;

2 - Laboratoire de Traitement de l'Information Médicale INSERM-UBO UMR 1101,  
Bâtiment 1, CHRU Morvan, 2, avenue Foch, 29609 Brest, Cedex, France.

3 - UBO, 3 Rue des Archives, 29238 Brest, France

4 - Uses and Acceptability Lab, [bcom](mailto:bcom@imt-atlantique.fr), 25, Rue Claude Chappe, 29280 Plouzané, France

5 - Service d'ophtalmologie, CHRU Morvan, 2 Avenue Foch, 29609, Brest, Cedex, France.

Corresponding author:

Vasilii Marshev, Batiment A1, 655 Avenue du Technopole, 29280 Plouzane, France

[vasili.marshev@imt-atlantique.fr](mailto:vasili.marshev@imt-atlantique.fr)

+33 767939880

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## Résumé

Objectif: le clignement joue pour l'œil un rôle protecteur important et l'utilisation d'ordinateurs a été associée à une réduction de la fréquence de clignement. Le but de cette étude était d'évaluer l'influence d'un écran de réalité virtuelle sur le clignement et l'épaisseur de la couche lipidique et de le comparer à celui d'un moniteur de bureau conventionnel.

Méthodes: Deux expériences ont été menées pour comparer l'impact de 20 minutes d'utilisation d'un casque de réalité virtuelle (FOVE), et de 20 minutes d'utilisation d'un moniteur de bureau, sur la fréquence et la durée des clignements (expérience 1, 15 participants) et l'épaisseur de la couche lipidique mesurée avec le Lipiview (expérience 2, 12 participants).

Résultats: Dans la première expérience, la fréquence de clignement ( $F(1,83) = 4,3, p = .04, \beta = .36$ ) et la durée ( $F(1,83) = 13, p = .001, \beta = .35$ ) ont augmenté avec le temps dans les deux conditions, mais aucune différence statistique n'a été trouvée entre les deux conditions (casque vs moniteur de bureau) ni pour la fréquence de clignement (rmANOVA  $F(1,11) = 0,01, p = 0,92$  ; casque: 15,1 clignements, IC95% : 12,6 à 17,6 clignements ; bureau: 14,6 clignements, IC95%: 13,6 à 15,7 clignements), ni pour la durée des clignements (rmANOVA  $F(1,11) = 4,534, p = 0,06$  ; casque: 205,75 ms, IC95%: 200,9 à 210,6 ms ; bureau: 202,82 ms, IC95%: 198,2 à 207,5 ms). Cependant, de fortes variations individuelles ont été observées. L'évaluation par questionnaire de cybermalaise et de fatigue visuelle n'ont pas montré de différences significative entre les deux conditions (questionnaire cyber-malaise SSQ:  $V = 46, p = 0,62$ ; questionnaire de fatigue visuelle VFQ:  $V = 15,5, p = 0,13$ ). Dans la deuxième expérience, l'épaisseur de la couche lipidique s'est avérée augmenter significativement après utilisation du casque de VR ( $F(1,18) =$

11,03,  $p = 0,004$ , casque: 76,2 nm, bureau: 58,8 nm).

Conclusion: En termes de recommandations, l'impact du casque de réalité virtuelle sur la durée et la fréquence de clignement pour une exposition modérée (20 ') est comparable à celui d'un moniteur de bureau conventionnel. Cependant, les fortes variations individuelles observées, le manque de tests fiables pour évaluer cette sensibilité individuelle, l'augmentation significative de l'épaisseur de la couche lipidique dans l'expérience 2, suggèrent l'intérêt d'une enquête plus approfondie, en particulier en considérant un temps d'exposition plus long et d'autres paramètres du film lacrymal.

**Keywords:** nictation, sécheresse oculaire, visiocasque, réalité virtuelle, LipiView, l'épaisseur de la couche lipidique

### **Abstract**

Purpose : Blinking plays an important role in protecting the eyes, and the use of computers has been associated with a reduction in the blink rate. The goal of this study was to evaluate the effect of a virtual reality headset on blinking and lipid layer thickness and to compare these data to those associated with a conventional desktop monitor.

Methods : Two experiments were performed to compare the effect of 20 minutes of use of a virtual reality headset (FOVE) and 20 minutes of use of a desktop monitor on the frequency and length of blinks (experiment 1, 15 participants) and on the thickness of the lipid layer as measured by Lipiview (experiment 2, 12 participants).

Results : In the first experiment, the blink rate ( $F(1,83) = 4.3, p = .04, \beta = .36$ ) and duration ( $F(1,83) = 13, p = .001, \beta = .35$ ) increased with time under both conditions, but no statistical difference was found between the two conditions (headset vs. desktop monitor) either for blink rate (rmANOVA  $F(1,11) = 0,01, p = 0,92$  ; headset: 15.1 blinks,

95% CI: 12.6 to 17.6 blinks; desktop: 14.6 blinks, 95% CI: 13.6 to 15.7 blinks) or for blink duration (rmANOVA  $F(1,11) = 4.534$ ,  $p = 0.06$ ; headset: 205.75 ms, 95% CI: 200.9 to 210.6 ms; desktop: 202.82 ms, 95% CI: 198.2 to 207.5 ms). However, strong individual variations were observed. Evaluation of simulator sickness and visual fatigue by questionnaire showed no significant differences between the two conditions (SSQ simulator sickness questionnaire:  $V = 46$ ,  $p = 0.62$ ; VFQ visual fatigue questionnaire:  $V = 15.5$ ,  $p = 0.13$ ). In the second experiment, the lipid layer thickness increased significantly after use of the VR headset ( $F(1,18) = 11.03$ ,  $p = 0.004$ , casque: 76,2 nm, bureau: 58,8 nm).

Conclusion: In terms of recommendations, the effect of virtual reality headsets on blink duration and frequency during a moderate exposure (20 minutes) is comparable to that of a conventional desktop monitor. However, the strong individual variations observed, the lack of reliable tests to evaluate this individual sensitivity, and the significant increase in lipid layer thickness in experiment 2 suggest the value of a more detailed investigation, in particular with consideration of a longer exposure time and other tear film parameters.

Keywords: blinking, dry eye, VR headset, virtual reality, LipiView, lipid layer thickness

## Introduction

In the last years, virtual reality (VR) head mounted displays (HMD) have been gaining popularity among the public, due to the arrival of several new and affordably priced commercial products. If VR HMDs are to replace the desktop screen (at least partially) in entertainment, as well as some professional applications, it is necessary to assess the possible implications they might bring in regard to user's experience and comfort. The issue of visual comfort has long been discussed in relation to computer screens, in particular their effect on blinking and eye fatigue<sup>1,2</sup> and on the development of dry eye disease<sup>3</sup> ("a common condition that carries significant patient morbidity and healthcare cost"<sup>4</sup>). Several studies have shown that observers exposed to the regular prolonged use of desktop screens become more susceptible to dry eye and computer vision syndromes, which may originate from regular reduction of blink frequency when using desktop screen<sup>5</sup>. In a recent study, Kim et al. found that blink rate decreased during two minutes long session when using a VR HMD when compared to using a desktop screen<sup>6</sup>.

Blink rate is, however, a parameter that shows significant dependency on environmental and individual characteristics<sup>1,2</sup>. For instance, while some studies observed increasing blink rate with the time spent on a task, which can be a measure of fatigue<sup>2,7,8</sup>, others invalidated this effect<sup>9</sup>. Contradictory results have also been reported with respect to the influence of mental load (Stert and Skelly<sup>8</sup> reported a decrease in blink frequency but not Yamada<sup>10</sup>) or task difficulty (decreased blink frequency reported by Stert and Skelly<sup>8</sup>, whereas not by Cho et al.<sup>11</sup>). For this reason, in this study, the goal of the first experiment was to compare the potential change in blink rate when using VR HMD to the one observed with a conventional desktop screen as a reference, as well as blink rate and blink duration change over 20 minutes of use. The performed measures also included

questionnaires to take into account the potential effect of cybersickness and eye fatigue. The details and results of the first experiment are described in Experiment 1 section . In addition, because blinking and dry eye condition are tightly linked to the tear film state<sup>3,12</sup> and particularly the most superficial layer of the tear film, i.e. the lipid layer<sup>13,14</sup>, the goal of the second experiment was to measure lipid layer thickness (LLT) before and after a session of either VR HMD or desktop screen use. The associated methods and results are presented in Experiment 2 section.

## **Experiment 1**

The goal of the first experiment was to assess the difference in blinking activity between two presentation methods: desktop screen (DS) (referred to as desktop condition) and VR HMD (referred to as helmet condition). While stimuli were designed to be as similar as possible in both conditions, several important aspects remained different due to peculiarities of the presentation methods: 1) ambient illumination (while in desktop condition, participants were seated in a dark room, in helmet condition, the stimuli were presented on a black background), 2) screen distance (see below), 3) image resolution (see below).

## **Methods**

### ***Apparatus***

The HMD used in the study was a FOVE helmet (FOVE, Inc., frame rate 70 Hz, resolution 1280×1440 each, field of view 90-100°). The FOVE integrates two cameras for eye tracking (70 Hz), which is a relatively novel feature for VR HMD devices. The DS was the display unit of the Tobii TX300 eye tracker (frame rate 60 Hz, resolution 1920×1080,

distance 60 cm, field of view 41.5°). Room temperature, humidity and lighting conditions, remained constant during the experiment. The HMD luminance and the DS luminance were adjusted to be as similar as possible (21.33 cd/m<sup>2</sup> in the helmet condition and 23 cd/m<sup>2</sup> in the desktop condition). When using the FOVE, the pupillary distance was not adjusted for each participant, as this feature was unavailable with this headset.

### ***Participants***

The required sample size was calculated using G\*Power3 software<sup>15</sup> for rmANOVA. In the experiment, one group sample went through two conditions (the helmet and the desktop conditions) giving one two-level factor. Type I error value was set to 0.05 and type II error value was set to 0.9. Effect size index was obtained from the study by Freudenthaler et al. who compared the blink frequency in two conditions: general conversation and visual display unit use<sup>12</sup>. The calculated value of effect size index of Cohen's d of 0,997 corresponded to effect size index Cohen's f of 0.5<sup>16</sup>. Other studies showing the dependence of blink rate on various parameters produced even higher effect size estimates. Given the abovementioned values, 13 subjects were necessary to achieve the required power. This number is also in agreement with previous studies<sup>17,18</sup>. 15 subjects were recruited for the experiment (26.8 years old; 95% CI: 21.7—32 years, 6 female and 9 male). All participants had best corrected visual acuity of 1 (in decimal) with or without correction and no record of cornea-related medical conditions or binocular vision issues. Participants were allowed to use their regular glasses if required. The study was carried out in accordance with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants.



### ***Design and procedure***

The participants went through 20 minutes of playing a simplified version of the 2D game “Flappy bird” in 2D, in two conditions: while wearing a HMD and in front of a DS, 60 cm away. Several studies suggest that 20 minutes of use of a VR HMD are sufficient to induce discomfort<sup>19</sup>. This duration presented a good compromise between the need for having a task long enough to possibly observe a decrease in blink rate (BR), and practicalities. The choice of this game was motivated by two reasons. Firstly, it required a sustained attention. BR has been shown to reduce with effort<sup>9</sup>, attention<sup>20</sup>, interest<sup>21</sup> and in view of the relatively short experiment duration, the circumstances were organized as to facilitate BR reduction. Secondly, it would not produce any cybersickness and its simple interface and availability made it easy to implement in both conditions with limited differences.

In the helmet condition, the game was presented on a "virtual" screen on a black background. The monitor in the desktop condition was positioned at 60 cm away from the viewer, in the helmet condition, the game was presented at the same distance to ensure that the game’s retinal projection was the same in both conditions. In addition, the game played on the DS was rendered at 640×480 (compared to 640×720 of each screen of the HMD) instead of the native screen resolution (1920×1080) to ensure similar pixel density per degree.

Although the game (“Flappy bird”) used in this study was designed to avoid any induction of cybersickness, Simulator sickness questionnaire<sup>22</sup> (SSQ) was used as a further precaution. The SSQ is a list of 16 questions to evaluate three categories of symptoms: nausea related symptoms, oculomotor symptoms and disorientation symptoms. In addition, the questionnaire developed by Bang et al.<sup>23</sup> was also used to assess visual discomfort (VFQ). This questionnaire based on study by Heo et al.<sup>24</sup> has the advantage of

being short and easy to fill out. Just before the test and right after it, the participants were seated in front of the DS while answering orally the experimenter's questions (SSQ and VFQ).

During the pretest and posttest interview, blink activity was measured using the Tobii TX300 eye tracker. When playing "Flappy bird" on the DS or the FOVE, blinking was measured respectively with the TX300 or the eye tracker integrated into the FOVE. Blinks were derived from the eye tracker data. Control for the closing percentage of the eye lid was not available with the FOVE's blink detection algorithm. Therefore, the eye closure was assumed whenever the eye tracker failed to recognize both eyes. Two criteria were used to consider absence of a pupil as a blink based on its duration: 1) bottom limit of 83 ms (following<sup>25,26</sup>), in order to filter out brief data losses, 2) top limit of 1 second (one of the criteria proposed by Stern et al.<sup>27</sup>) to exclude other irrelevant events.

In order to limit the number of subjects and due to significant individual variability of BR in people (see Introduction and Stern et al.<sup>1</sup>), a within-group design was chosen. To avoid any possible influence of the order of the tests, half of the participants went through the helmet condition first, the other half were tested with the DS first. Two experimental sessions for both conditions were taken on two separate days to avoid any possible cross influence.

To assess if the blinking data from the FOVE and TX300 are in agreement, two measurements with two participants were performed to compare the counted blinks estimated by the eye trackers to those made by a human observer during two minutes playing sessions. The observer would directly watch the subject's eyes when using the TX300 or watch the videos recorded by the cameras of the FOVE's eye tracker using the FOVE debug application on a separate screen. Results (see Table 1) show that

measurements can differ from the ones measured by an observer, and the FOVE seems somewhat less consistent with the experimenter's observations than the Tobii. Various reasons can contribute to this discrepancy in blink count, such as different proprietary algorithms. Observer's blinks and judgements about whether a blink was complete (covered the whole pupil) can affect the observer's count. Another possibility could be that the quality of the eye tracking system built in the FOVE helmet may be of poorer quality than that of the TX300, thus widening the discrepancy in the measurements made by the observer and by the FOVE eye tracker. Yet, since eye trackers based analysis has been used lately in studies dedicated to blinking activity<sup>12,26</sup>, this method was used to analyze blinking as well. To avoid misconclusions due to the possible bias in the eye trackers' measurements, the blink metrics measured by Tobii just before and immediately after the game session were compared (pretest and posttest comparison).

### ***Analyses***

Each test condition (helmet and desktop conditions) consisted of three phases: pretest (included a questionnaire-based interview), test (playing the game) and posttest (included a questionnaire-based interview). In each phase of the experiment, eye blinks were recorded. Therefore, the data included two subsets: blinking activity and questionnaire results.

Blinking was analysed in two aspects: BR and blink duration (BD). Blinking during the test phase was analysed in five minutes intervals (thus, four intervals). Average number of blinks per minute was calculated for each five minute interval. Therefore, for the test, each participant's data were treated as four pairs of BR and BD averaged for each of the four five-minute intervals. Only the blinks recorded during the first two minutes were used in the

analysis for the pretest and posttest interviews, as the duration of the interviews varied with participants. To compare BR in the pretest phase and the posttest phase in both conditions, the BR recorded in the pretest was subtracted from the BR recorded in the posttest. For BD analysis, average BD recorded in pretest was subtracted from that recorded in posttest.

## Results

The data of three participants were excluded from the analysis, because their blink registration data were too noisy to efficiently distinguish actual blinks from data losses which occurred during the tests and resulted in eye trackers' failure to register any blinks in long time intervals, such as three consecutive minutes.

BR for all participants during the game in both conditions (i.e., desktop and helmet data averaged together) was 14.9 blinks; 95% CI: 13.5—16.2 blinks (see Table 2), BD was 198.8 ms; 95% CI: 195.3—202.3 ms, which is similar to what has been reported in previous studies<sup>28</sup>.

Repeated measures ANOVA was used to investigate how BR and BD varied in both conditions and with time on experiment (2 (conditions) × 4 (five-minute intervals)) during the test phase. The analysis did not show significant difference in BR (rmANOVA  $F(1,11) = .01$ ,  $p = .92$ ) between the helmet condition (15.1 blinks; 95% CI: 12.6—17.6 blinks) and the desktop condition (14.6 blinks; 95% CI: 13.6—15.7 blinks). Neither the difference in BD between the helmet condition (205.75 ms; 95% CI: 200.9—210.6 ms) and the desktop condition (202.82 ms; 95% CI: 198.2—207.5 ms) was significant (rmANOVA  $F(1,11) = 4.534$ ,  $p = .06$ ).

Both parameters increased significantly with time (rmANOVA  $F(1,11) = 9.19$ ,  $p = .01$  for BR, rmANOVA  $F(1,11) = 6.4$ ,  $p = .03$  for BD), as illustrated, respectively, in Fig. 1 and Fig.

2. To support this observation, linear mixed-effects regression analysis was performed to model BR and BD as functions of time. To account for between-subject variance, a random intercept for each participant was included. To assess the effect of time, two models were compared: one with time as a fixed effect and one without. P-values were computed using Kenward-Roger approximation; this method was chosen due to the comparatively small sample size. The models confirmed an increase in BR ( $F(1,83) = 4.3, p = .04, \beta = .36$ ) and in BD ( $F(1,83) = 13, p = .001, \beta = .35$ ) with time.

Pretest and posttest BR comparison (the BR in pretest subtracted from the BR in posttest) did not reveal any significant differences (rmANOVA  $F(1,11) < .001, p = .98$ ) between the helmet condition (1.2 blinks; 95% CI: -3.5—+5.8 blinks) and the desktop condition (1.3 blinks; 95% CI: -4.2—+6.7). The comparison of BD (the BD in pretest subtracted from the BD in posttest) also did not show significant difference ( $F(1,11) < .001, p = .92$ ) between the helmet condition (-4.67 ms; 95% CI: -34.8—+25.4 ms) and the desktop condition (-7.23 ms; 95% CI: -75.7—+61.2).

Regarding the questionnaires measuring eye fatigue (VFQ) and discomfort (SSQ) induced by the use of HMD or DS, the difference between the posttest and the pretest scores was calculated to compare the conditions (helmet vs desktop) using the Wilcoxon paired test. The results did not show significant differences between the conditions (helmet vs desktop) for both questionnaires (SSQ:  $V = 46, p = .62$ ; VFQ:  $V = 15.5, p = .13$ , see Fig. 3).

In view of the absence of differences between the two conditions and the importance of individual variations in blinking (see previous sections), individual results were analyzed to see if for some of the participants BR varied more significantly than for others, depending on the test conditions (see Table 3). In this analysis, 20 BR values (for each minute) were

taken for each participant to obtain more reliable datasets. False discovery rate correction for multiple comparisons was used. The data show that among 12 subjects, who participated in the experiment, four demonstrated significantly more blinks in the helmet condition, seven subjects showed significantly more blinks in the desktop condition, and in one participant, no significant difference was found in BR between the conditions.

In order to see if questionnaire scores reflected this individual variability, questionnaire score change and BR differences were tested between the conditions for correlation with Spearman correlation coefficient. No significant correlation was found for both questionnaires (SSQ:  $r_s = .29$ ,  $p = .35$ ; VFQ:  $r_s = -.16$ ,  $p = .61$ ).

## **Experiment 2**

In Experiment 2 LLT before and after a video game session was measured. The lipid layer “is the outermost layer of the tear film”<sup>4</sup> and its thickness has been shown to depend on blinking frequency<sup>13</sup> and to correlate with dry eye symptoms severity<sup>29</sup>. Lipid layer is thought to slow down the tear film evaporation rate, therefore, reduced LLT or inconsistency of its spread across the cornea due to BR decrease can lead to dry eye symptoms<sup>14</sup>. Subjects were divided into two groups, one of which played the game wearing the FOVE HMD (the helmet condition) and the other played the game in front of a DS (the desktop condition).

## **Methods**

### ***Apparatus***

The same FOVE helmet was used as in Experiment 1. The instrument used to assess LLT was the LipiView® ocular surface interferometer (TearScience Inc, Morrisville, NC). During

the measurement, the participant is seated in front of the apparatus and places his head on a chin rest. The built-in multi-wavelength light sources emit light into the participant's eye while the built-in cameras capture a picture of the eye. The light reflected from the tear film is used to compute the light interference patterns to infer the thickness of the outermost lipid layer of the tear film<sup>30</sup>. Measurements which exceeded the maximum value accessible by the apparatus (100 nm) were discarded from the analysis. All the measurements were performed by the same specialist at the Brest Regional Hospital-University Centre.

### ***Design and procedure***

Participants played the game "Flappy bird" for 20 minutes as described in Experiment 1. Two groups of subjects participated in this experiment. One group played the game on a DS, the other group played it wearing the FOVE HMD. LLT (both eyes) was measured by the same trained orthoptist right before (pretest) and right after (posttest) playing the game. Only right eyes data were used in the study.

To double check the repeatability of the data provided by the apparatus, a small study was carried out with four subjects (including one author) (25.5 years old; 95% CI: 18.4—32.6 years, 3 female, 1 male) who were tested by the same observer four times during the day between 10 a.m. and 4 p.m. with two hours intervals in same conditions (same room, same lighting, with humidity and temperature controlled by an airconditioner). Data of one participant were excluded (LLT value exceeded the maximum accessible by the apparatus (100 nm)). Coefficient of repeatability was 9 nm for the left eye and 8 nm for the right eye. These results are in agreement with another study<sup>4</sup> which showed that "when a single observer repeated the imaging on the same day, the coefficient of repeatability was 16 nm and the 95% limits of agreement were between -11 nm and 18 nm".

## ***Participants***

The desktop group consisted of 12 subjects (including 3 authors) (31.3 years; 95% CI: 25.5—37.2 years, 6 female and 6 male). The helmet group consisted of 12 subjects (including 3 authors) (32.8 years; 95% CI: 25.9—39.7 years, 6 female and 6 male). Data of two subjects were discarded from the helmet group due to value of LLT exceeding the maximum value measurable with LipiView (100 nm). In order to even out the sizes of the samples in the two groups, data of two randomly chosen participants in desktop group also were not included into the analysis.

The required sample size was calculated using G\*Power3 software<sup>15</sup> for 2×2 between-within subject ANOVA. The within-subject factor was represented with the measurement stage (pretest or posttest). The between-subject factor was represented with the condition (helmet or desktop). Type I error value was set to 0.05 and type II error value was set to 0.9. In absence of studies with similar designs, methods and conditions that could be used as reference for expected effect size estimation, the effect size was considered big (Cohen's  $f$  of 0.5) due to high test-retest reliability of the used measuring technique and the precision of the apparatus. The calculated sample size necessary to find the significant interaction of the two factors was 20. It corresponds to the resulting 20 participants (10 in each condition) whose data that were analyzed.

All participants had normal or corrected to normal vision and no record of cornea-related medical conditions. Participants were allowed to use their regular glasses if required. The study was carried out in accordance with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants.



## Results

Initial LLT (before the experiment) was 57.2 nm; 95% CI: 53.3—61.1 nm and it reached 66.5 nm; 95% CI: 62.25—70.8 nm afterwards, which was a little lower than data reported previously<sup>31</sup> (average 89.8 nm with standard deviation 42.5). Mixed effects ANOVA was used to test the effect of the experiment phase (pretest or posttest) and condition (helmet or desktop) on LLT.

The results showed a significant interaction between phase and condition ( $F(1,18) = 9.35$ ,  $p = .02$ ). Further analysis revealed significant increase in LLT in both conditions (helmet:  $F(1,9) = 26.18$ ,  $p < .001$ , desktop  $F(1,9) = 14.22$ ,  $p = .004$ ). Also, it showed comparable initial values of LLT between the conditions (pretest:  $F(1,18) = 0.77$ ,  $p = .39$ ) and significant difference after 20 minutes of the session (posttest:  $F(1,18) = 11.03$ ,  $p = .004$ ) with a higher LLT value found in the helmet condition (58.8 nm in desktop condition, 76.2 nm in helmet condition) (see Fig. 4).

## Discussion

Computer vision syndrome is defined by the American Optometric Association as the combination of eye and vision problems associated with the use of computers<sup>32</sup>. These problems include eyestrain, tired eyes, irritation, redness, blurred vision and diplopia. One of the possible causes of computer vision syndrome is the reduction of the BR that contributes to a poor tear film quality and temporary stress of the cornea. Most studies concerning computer vision syndrome focused on the use of conventional computer screens<sup>5</sup> but little is known about the risk of computer vision syndrome symptoms when using VR HMD. Kuze and Ukai<sup>33</sup> conducted a pretest-posttest questionnaire study to compare the visual fatigue effect of HMD and DS use, but their system used 3D stimuli on

the contrary of this study. In the present study, the choice of the 2D stimuli instead of 3D stimuli was dictated by the need to investigate the possible outcomes of the presentation circumstances and to isolate them from the influence of 3D presentation aftereffects, such as vergence-accomodation conflict and cybersickness.

In Experiment 1, the goal was to investigate the impact of HMD use on BR, BD, cybersickness and eye strain and compared it to that of DS use. In terms of BR and BD, the present results are in agreement with literature<sup>2</sup> with respect to the fact that BR and BD increase with time spent on a task. However, the change in BR and BD after the game compared to the base level (pretest-posttest comparison) was not statistically significant. In the present study, the game presentation time was comparable to other studies<sup>33</sup>, but, perhaps, too short to allow observing a significant change in BR increase between the two conditions.

On the contrary to Kim et al.<sup>6</sup>, the present results did not highlight any significant impact of the viewing method on BR and BD. This discrepancy may be explained by the different procedures: 1) the screen distance (0.6 m here and 1 m in the study by Kim et al.<sup>6</sup>), 2) the stimuli (here, participants performed a task that required them to pay attention to the scene to fulfill the task), 3) the algorithm used to count blink, and, perhaps, most of all 4) the test duration (20 minutes here and 2 minutes in Kim et al.<sup>6</sup>). However, the results of the present study are in agreement with Kuze and Ukai<sup>33</sup> who did not find differences in terms of induced eye fatigue (assessed by questionnaire scores) despite using a possibly more tiring stimulus (stereoscopic). Significant individual variations in BR between the conditions occurred in 11 of 12 subjects suggesting that personal recommendations are needed when regular use of any of the presentation techniques is considered. At the same time, according to the correlation analysis, questionnaire scores did not follow these individual

variations, suggesting that questionnaires used in this study may not be sensitive enough to measure these individual susceptibilities. (The questionnaires were filled out in the first five minutes past viewing (according to Ames et al.<sup>34</sup>), which allowed to rule out the possibility that symptoms had dissipated by the time the subjects filled the questionnaires.) The goal of experiment 2 was to measure the change in eye tear film LLT after DS and HMD use. According to the present results, LLT increased in both conditions, whereas no change was expected (following the results of experiment 1) or a reduction (e.g., due to reduced BR). A possible explanation would be that participants, having deprived themselves from blinking while playing, felt necessary to blink intensively after the experiment, producing excessive LLT reinforcement before the second measurement was made, as extensive blinking has been shown to cause significant increase in LLT<sup>13</sup>.

Secondly, the experiment revealed higher degree of change of LLT after HMD use compared to DS use. In this study, the temperature and humidity conditions were not measured, but controlled by providing same environment for all participants. These environmental factors have been shown to have the influence on tear film state and, in particular, on LLT. For instance, Abusharha and colleagues<sup>35</sup> conducted an experiment varying the temperature in a controlled chamber and showed increase in LLT and evaporation rate as a consequence of increase of temperature. Korb et al.<sup>36</sup> measured the effect of humidity on LLT. They compared the LLT in an eye in the room humidity (40-50% of relative humidity) to that in an eye isolated with goggles with 10 drops of saline added onto the mounting to increase humidity. The results<sup>36</sup> showed that in the eye presented with higher humidity, LLT increased significantly compared to the eye in the room humidity both during the period of different humidity and as far as 60 minutes after removing the goggles. Presumably, the isolated chamber of the HMD might preserve higher temperature

and humidity because of the face skin and sweat evaporation, which might produce similar effect to that in the two studies<sup>35,36</sup>. It may also be an evidence for a more apparent manifestation of a reactive mechanism protecting the ocular surface from exposure to blink reduction, however this claim would require a thorough experimental clarification.

In conclusion, the present study addressed the issue of blinking during use of VR HMD. On the contrary to a recent study<sup>6</sup>, the present results did not show any statistically significant differences between DS and HMD in terms of blinking. However, strong individual variations were observed in all subjects but one. In view of these results, further investigation considering longer exposure time and more “natural” use (i.e. in the design used here the two conditions were as similar as possible, but in practice, VR games tend to be more visually demanding than the ones played at the DS) would be of interest, also considering additional tear film statistics<sup>37</sup>.

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### **Disclosure of interest**

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**Figure 1:** Blink rate throughout the game session in the two conditions. Number of blinks per minute (blink rate, BR) averaged for five-minute intervals across the participants (N = 12) while playing a game in two conditions (while using a virtual reality headset and desktop screen) with regression lines is plotted. No significant difference between the conditions was found. Blink rate increases with time. Dots indicate mean blink rate for the previous 5 minutes across all the participants for the helmet condition, and triangles indicate blink rate for the desktop condition. The dashed and solid vertical lines represent the 95% confidence intervals for the helmet and desktop conditions, respectively. Also, linear models were fitted for the helmet (dashed) and the desktop (solid) conditions.

**Figure 2:** Blink duration throughout the game session in the two conditions. The duration of blinks averaged in five-minute intervals across the participants (N = 12) while playing a game in two conditions (while using a virtual reality headset and desktop screen) with regression lines is plotted. No significant difference between the conditions was found. Blink duration increases with time. Ordinate: blinks duration is scaled on the ordinate axis, abscissae: time into the test. Dots indicate mean duration for the previous 5 minutes across all the participants for the helmet condition and triangles indicate blink rate for the desktop condition. The dashed and solid vertical lines represent the 95% confidence intervals for the helmet and desktop conditions, respectively. Also, linear models were fitted for the helmet (dashed line) and the desktop (solid line) conditions.

**Figure 3:** Questionnaire scores change after the game session in the two conditions. The score change for the two questionnaires used in the study (simulator sickness questionnaire (SSQ) and questionnaire of visual fatigue (Visual Fatigue)) averaged across

the 12 participants after 20 minutes long game session wearing a virtual reality headset (helmet condition) and in front of a desktop screen (desktop condition) is plotted. Score change was calculated by subtracting the score measured before the test from the score measured after the test. The change was not found statistically significant. The data in the desktop condition is plotted with a solid line, and the data in the helmet condition is plotted with a dashed line.

**Figure 4:** Lipid layer thickness measurements before and after the game session in the two conditions. Lipid layer thickness averaged across all participants before and after 20 minutes of playing the game wearing virtual reality headset (helmet) and in in front of a desktop screen is plotted. Lipid layer thickness increased significantly with time. Also, it increased at a higher rate with the virtual reality headset. Lipid layer thickness is scaled on the ordinate axis, the measurements done before the experiment (pretest, left) and after 20 minutes of playing the game in virtual reality headset (posttest, right). The data in the desktop condition is plotted with a solid line, and the data in the helmet condition is plotted with a dashed line.

Eye tracker	Subject	BR measured by	
		observer	eye tracker
Tobii	1	71	84
		71	85
	2	49	49
		71	85
FOVE	1	31	47
		49	55
	2	18	38
		33	15

Table 1: Comparison of BR measurements done by an observer and by the two eye trackers used in the study

Subject	Mean BR (Desktop/Helmet)				
	0-5 minutes	5-10 minutes	10-15 minutes	15-20 minutes	Mean
1	1.4/2.4	2.2/7	2.8/8.4	3/4.2	2.4/5.5
2	19.6/38	23.8/21.8	22/47.8	21/72.2	21.6/45
3	21/48.8	20.6/38.8	22/69.6	21/69.4	21.2/56.7
4	10.8/2.6	9.4/2.8	9.8/2.6	5.2/1.6	8.8/2.4
5	15.2/19.4	14.4/22	15.2/26	17.6/26	15.6/23.4
6	10.4/2.6	12.8/3.8	12.8/2.2	10.8/6.4	11.7/3.8
7	20.8/11.2	27.6/10.4	30.6/10	37.2/9.8	29.1/10.4
8	10.6/9.8	12.6/17.4	17.6/14.6	16.2/15.2	14.3/14.3
9	15/4.2	17.8/6.6	19.6/9.8	22/6.8	18.6/6.8
10	13/9	14/3	15.2/12	15.6/12.4	14.5/9.1
11	8.2/1	7.8/0.6	11.2/4	6.8/3	8.5/2.2
12	9.8/2.2	6.4/2	7.2/2.4	14.8/1.2	9.6/2
Mean±Standard Deviation	13±5.7/12.6±1 5.5	4.1±7.4/11.4±1 1.5	15.5±7.5/17.4 ±20.9	6±9.2/19±25.2	14.6±7.4/15.1± 18.7

Table 2: Mean BR (number of blinks per minute) for 5 minutes intervals throughout the experiment for each condition and for each subject

<b>Subject</b>	<b><i>F</i></b>	<b>Corrected <i>P</i></b> <b>(False Discovery Rate)</b>	<b>Mean BR; 95% CI (Helmet / Desktop), blinks</b>
1	22.11	< .001	5.5; 3.88—7.12 / 2.35; 1.8—2.9
2	16.72	< .001	45; 33.56—56.35 / 21.6; 20.09—23.11
3	64.2	< .001	56.65; 47.59—65.71 / 21.15; 19.6—22.7
4	22.15	< .001	2.4; 1.59—3.21 / 8.8; 6.08—11.52
5	18	< .001	23.35; 20.06—26.64 / 15.6; 13.92—17.28
6	63.71	< .001	3.75; 1.97—5.53 / 11.7; 10.56—12.84
7	72.21	< .001	10.35; 9.11—11.6 / 29.05; 24.91—33.19
8	< 0.0001	> .99	14.25; 11.24—17.26 / 14.25; 12.3—16.2
9	80.54	< .001	6.75; 5.1—8.4 / 18.6; 16.61—20.6
10	14.53	.001	9.1; 6.46—11.74 / 14.45; 12.52—16.39
11	100.44	< .001	2.15; 1.27—3.03 / 8.5; 7.18—9.82
12	30.62	< .001	1.95; 1.25—2.65 / 9.55; 6.88—12.23

Table 3: Participants-wise analysis of the difference between the conditions

Table 3. Participants-wise analysis of the difference between the conditions.









