Effect of head-mounted displays on the tear-film

by

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75767

Abstract

Purpose: The use of computers spread among the population, both for work and leisure purposes. This poses an increased risk factor for dry eye disease, a multifactorial disease influencing the surface of the eye. With the recent increasing usage of head-mounted displays, it is critical to determine whether or not they have the same impact on the tear film as conventional screens.

Methods: The experiment was divided into three parts, where ten subjects participated. A baseline measurement was taken on the first day, and two additional measurements were retaken after 90 minutes of usage of a head-mounted display or a conventional screen.

Results: No statistically significant differences were found in the impact on the tear film, neither in blink frequency nor duration while using a head-mounted display. Humidity and temperature in the periocular environment increased in the first 30 minutes of HMD usage, then remained stable while the oxygen level decreased. In comparison, temperature and humidity were lower, with oxygen levels increasing while using a conventional screen to become stable over 90 minutes. Subjects perceive subjectively less dry eye after using an HMD.

Conclusions: Although no final conclusions can be drawn from the results, there is a tendency toward HMDs having a slightly better impact on the tear film than conventional screens.

Keywords: Virtual reality; dry eye; tear film; Blinking;

Abstract (German)

Ziel: Die Nutzung von Computern ist in der Bevölkerung weit verbreitet, sowohl bei der Arbeit als auch in der Freizeit. Dies stellt einen erhöhten Risikofaktor für die Erkrankung des trockenen Auges dar, eine multifaktorielle Erkrankung, die Oberfläche des Auges beeinflusst. Angesichts der zunehmenden Verwendung von Head-Mounted-Displays ist es von entscheidender Bedeutung, ob diese denselben Einfluss auf den Tränenfilm haben wie herkömmliche Bildschirme.

Methoden: Das Experiment war in drei Teile unterteilt, an denen zehn Probanden teilnahmen. Am ersten Tag wurde eine Basismessung durchgeführt, und zwei weitere Messungen wurden nach 90 Minuten Nutzung eines Head-Mounted Displays oder eines herkömmlichen Bildschirms vorgenommen.

Ergebnisse: Es wurden keine statistisch signifikanten Unterschiede in der Auswirkung auf den Tränenfilm festgestellt, weder in der Blinzelfrequenz noch in der Blinzeldauer während der Nutzung eines kopfgetragenen Displays. Luftfeuchtigkeit und Temperatur in der periokularen Umgebung stiegen in den ersten 30 Minuten der HMD-Nutzung an und blieben dann stabil, während der Sauerstoffgehalt sank. Im Vergleich dazu waren Temperatur und Luftfeuchtigkeit niedriger, wobei der Sauerstoffgehalt bei der Verwendung eines herkömmlichen Bildschirms anstieg und sich über 90 Minuten stabilisierte. Die Probanden nehmen subjektiv weniger trockene Augen nach der Verwendung eines HMD wahr.

Schlussfolgerung: Obwohl aus den Ergebnissen keine endgültigen Schlüsse gezogen werden können, besteht die Tendenz, dass sich HMDs etwas besser auf den Tränenfilm auswirken als herkömmliche Bildschirme.

Schlüsselwörter: Virtuelle Realität; trockenes Auge; Tränenfilm; Blinzeln;

You know, I'm something of a scientist myself.

Spider-Man (2002)

Acknowledgement

At this point I would like to thank the people without whose help this bachelor thesis could not have been written.

First of all, I would like to thank the ZEISS Vision Science Lab and Prof. Dr. Siegfried Wahl for the opportunity to write my thesis there.

Many thanks also to Prof. Dr. Anna Nagl, my supervisor in Aalen, for her support and for recommending me for this thesis.

I would also like to thank my supervisor in Tübingen, Dr. rer. nat. Miguel García García, for his support in the last six months, whether it was proof-reading the thesis over and over or giving me the (definitely) needed support in MATLAB.

Special thanks to my friends Johannes, Jonas, Marvin, Nina and my siblings Xenia and Yul for the emotional support and encouragement while studying and writing my thesis, but also for the last-minute proof-reading of it.

Finally, huge thanks to my parents for their unconditional support on my way. Without them, all of this would have been impossible.

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List of Abbreviations

CVS	Computer Vision Syndrome
DED	Dry Eye Disease
DEWS	Dry Eye Workshop
dpt	Diopters
Fps	Frames per second
HDMI	High-Definition Multimedia Interface
HMD	Head Mounted Displays
LIPCOF	Lid-Parallel Conjunctival Folds
NIBUT	Non-invasive tear film break-up time
OD	Oculus Dexter
OLED	Organic Light Emitting Diode
OS	Oculus Sinister
OSDI	Ocular Surface Disease Index
SD Card	Secure Digital Memory Card
SSH	Secure Shell
TBUT	Tear film Break-Up Time
USB	Universal Serial Bus
VDT	Visual Display Terminal
VDU	Visual Display Units
VR	Virtual reality

Motivation

Dry eye is a disease of the eye on which a deficit of tear film appears due to several reasons, including a faulty composition of the same. In addition to symptoms such as burning or itching eyes, as well as redness of the conjunctiva and the limbus, there are further consequences such as light sensitivity or even drying of the cornea up to scarring. Dry eye can have a big impact on the quality of life and work productivity of the affected persons, but it can also influence their mood and confidence (1).

Whether for work, study or leisure, computers usage has increased steadily in the last decades (2). It has been known for some time that computer work can lead to dry eyes (3). Similarly, virtual reality (VR) technology is increasingly rising and could be integrated into everyday life, much like Facebook's "infinite office" virtual office space unveiled in 2020 and additional possibilities like virtual meeting rooms.

Lockdowns during Covid have significantly increased the usage of digital displays, which might have led to more computer vision syndrome symptoms, including the dry eye (4). While it is well known that working with visual display units, also known as VDU, has a negative effect on the tear film, and there are many studies on this, there are only a few studies examining the impact of head-mounted displays on the tear film.

Computer vision syndrome (CVS) combines eye and vision problems. It can be caused by environmental factors or a reduced blink rate, coming with the usage of computers and is resulting in visual discomfort and lower productivity (5).

Therefore, this study aims to compare the influence of conventional computer work environments and head-mounted displays on the tear film and whether head-mounted displays have a similar, better, or worse effect on the tear film than conventional monitors over a relatively short time span.

1 Introduction

1.1 The tear film

The tear film is a thin liquid layer that bathes the outer area of the eye and protects it against foreign bodies. It has different functions, like lubricating the ocular surface, supplying nutrients to the avascular cornea, defence mechanisms or avoiding friction while blinking (6). A neuronal reflex loop regulates the tears' production. For example, if the corneal epithelium is injured, more tear film production is elicited and its content changes to promote wound healing (7).

Furthermore, the tear film smooths the corneal surface and protects it, as it also contains anti-inflammatory and anti-infective substances.

1.1.1 Tear film composition and roles

As shown in Figure 1, the tear film is a thin film of fluid in front of the cornea. In simple terms, the eye's tear film consists of three principal layers, a mucin layer, which adheres to the eye by forming a hydrophilic surface, an aqueous layer produced in the lacrimal gland, and a lipid layer that prevents the tear film from drying out (8).
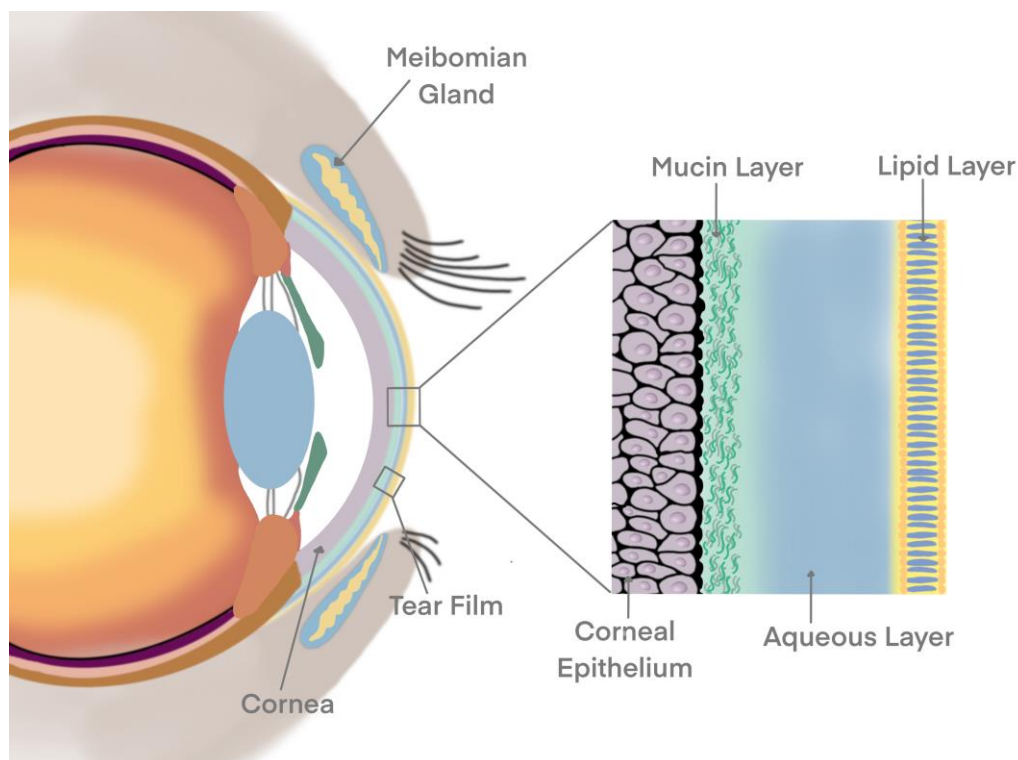

Figure 1 Tear film layers

The mucin layer is produced by conjunctival goblet cells and conjunctival and corneal epithelial cells, while the aqueous layer is begotten at the lacrimal glands. On the other hand, the meibomian glands produce the lipid layer, which is supposed to reduce the evaporation rate (7). The mucin layer, the innermost one, ensures the adhesion of the tear film to the eye and, among other things, also compensates for irregularities in the corneal surface. Furthermore, it functions as a lubricant for the eyelids (9). The aqueous layer also contains some dissolved mucins and provides the cornea with the necessary nutrients, such as proteins (10).

A tear film dysfunction could lead to increased evaporation, instability, and reduced visual acuity (11). Aqueous deficiency, meaning that not enough aqueous layer is produced, can happen due to lacrimal gland dysfunction. Usually, the lipid layer protects the tear film's surface. If it is not working efficiently enough, the eye's surface dries out due to a faster tear film break up time, followed by faster evaporation, which might lead to dry eye, as explained in the following chapter.

1.2 Dry eye

Dry eye is a disease usually caused by a dysfunctionality of the tear film, its components, or its production. It is also known as keratoconjunctivitis sicca, and it is usually noticeable by burning eyes, a foreign body sensation or redness of the conjunctiva. Several reasons can cause dry eye (12).

The Dry eye workshop defined dry eye in 2017 as:

"… a multifactorial disease of the ocular surface characterised by a loss of homeostasis of the tear film, and accompanied by ocular symptoms, in which tear film instability and hyperosmolarity, ocular surface inflammation and damage, and neurosensory abnormalities play etiological roles." (13)

1.2.1 Dry eye aetiology

The foremost reason for dry eye is deficient tear production, although an excessive production of tears can also cause it. Both lead to instability of the lipid layer of the tear film (14). The thickness of this lipid layer does play a role, as a thinner lipid layer increases the likelihood of dry eye (15). Dry eye has other consequences besides the unpleasant perception, such as decreased visual performance. For example, Szczotka-Flynn et al. found that instability of the tear film can lead to deterioration of contrast vision (16).

There are three different forms of dry eye: aqueous deficient dry eye, evaporative dry eye, or a mixture of them. The evaporative form is the most common. In this case, the lacrimal gland is working normally, but due to, for example, a deficient lipid layer or a meibomian gland dysfunction, there is excessive evaporation of the tear film. On the other hand, the rarest form, the aqueous deficient form, is caused by insufficient tear film, e.g., due to a reduced working lacrimal gland (17,18). A third form is a mixed form. The evaporative form is caused mainly by

a meibomian gland dysfunction, which sometimes leads to increased tear film production, which can be followed by a reduced tear secretion, leading to the mixed form of dry eye disease (19).

1.2.2 Risk factors for dry eye

Dry eye disease is influenced by natural factors such as age, gender, race, hormones and nurture or environmental factors like using computers, habitual contact lens wearing, or low humidity environments (20). Sex, thyroid, and insulin hormones do play a significant role in impacting the dry eye. The female sex is a risk factor not only for dry eye disease but for other diseases like Sjögren syndrome (which is, in turn, another risk factor for dry eye) (21). Besides these points, wearing contact lenses is considered a risk factor for dry eye since they need to get hydrated and lubricated by the tear film. Homeostasis of the tear film can be disturbed by contact lens wear. (22).

1.2.3 Solutions for dry eye

To indicate the proper therapy for dry eye disease, one does need a differential diagnosis and causal research to treat it efficient. There is no gold standard yet to diagnose dry eye. The main problem seems to be that not all patients serve the sensitive thresholds of different parameters like OSDI, Schirmer and TBUT. In general, the existing questionnaires can be used for screening but not diagnosing (23).

Depending on the cause of the dry eye, there are several options for therapy. Artificial tears are the most prevalent starting treatments for tear insufficiency. On the other hand, there are different substitutes like aqueous supplementation or lipid supplementation and overnight treatments, depending on dry eye disease type. Likewise, blink animation programmes, Omega-3 fatty acids, and an ergonomic office space seem to be decreasing dry eye symptoms (24). A less used therapy is punctal occlusion which can be done temporarily or permanent. Especially with blocked glands, eyelid hygiene or warm compresses are recommended. Depending on the severity of the dry eye, antibiotics or steroids, or therapeutic contact lenses can be used (25). In severe cases of keratoconjunctivitis sicca, surgical intervention might be needed (12).

To prevent dry eye disease (DED) appearance and lessen the symptoms, the general public should be aware of the risks. Health education plays a major role here. Since environmental influences play a role, measures should be taken when more exposed, i.e. work and leisure time. Particulate matter poses a risk for DED and could be reduced through policy measures or by improving the ergonomic design of the workplace, with particular attention to factors like humidity, screen brightness and ambient light. In addition to these general measurements, screening risk groups and people who spend a lot of their time in front of a screen due to their job can help minimise the risk of dry eyes, as early interventions could take place (26).

1.2.4 Dry eye and computer work

Computer vision syndrome is a phenomenon that repeatedly occurs in connection with dry eye. It has been known that working at a computer screen reduces the blinking rate, which leads to a rupture of the tear film, and in the end, to dry eyes (27). Besides reducing the blink rate, incomplete blinking also increases while working with computers, deteriorating the tear film stability and exposing the ocular surface (20). Computer vision syndrome is usually presented with blurry vision, a diminished power of accommodation and problems with near vision, such as removing the near point or deviation of phoria (28). Not only is the visual comfort reduced, but productivity also suffers from dry eye (29). The office environment and computer work are both suffering its impact as well.

Furthermore, an increased airflow, e.g. caused by air conditioning, can cause eye discomfort while working (30). In some cases of dry eye, blinking exercises can be used to improve the situation and protect the eyes from the impact that digital devices have on the tear film (31). Prevention of dry eye while using VDTs includes blinking deliberately as well as naturally, but also environmental modifications. The use of digital devices should also play a role during eye exams by professionals to identify people who have a higher risk to suffer from dry eye disease (3).

1.1.2 Dry eye and head-mounted displays

Head-mounted-displays were already mentioned in 1968 (32). In conjunction with virtual reality (VR), these devices are mainly used in gaming, medical, military, education, and the training of different skills (33–37). Even though they have changed a lot in technical and optical aspects since then, there are still open questions to research. Since the use of head-mounted displays in everyday office life is not yet very widespread, even though the interest in those devices is growing, there are not too many research results on the ergonomics of these devices and their effect on the tear film.

Kim et al. found a decreasing blink rate with HMD usage compared to the usage of a conventional screen (38). Marshev et al., on the other hand, measured the lipid layer before and after gaming for 20 minutes. They found a thicker lipid layer after using an HMD than a conventional screen and no significant difference in fatigue and discomfort, but they also found high individual variations. However, they only measured for a short period of 20 minutes, and no other measurements regarding the tear film were reported (39). In comparison, another study found more subjective dry eye symptoms after using an HMD than after smartphone usage for two hours. Here, no measurements of the tear film followed, and only a questionnaire was used to detect the symptoms. Other changes in accommodation and stereopsis were also found in this study (40). Turnbull et al. measured the temperature on the outer eyelid every five minutes, non-invasive tear film break-up time (NIBUT), tear meniscus height and the tear film lipid layer grade were measured with a keratograph. Those measurements were taken

after 40 minutes of using an HMD and a conventional screen. Nonetheless, they did not measure humidity or oxygen levels, despite assuming a decreased airflow in the headset. A slightly increasing temperature and so-called positive effects on lipid layer thickness and NIBUT were found (41).

2 Material and methods

2.1 Ethics

This study adheres to the tenets of the Helsinki Declaration (2013) and later amends. The ethics authorisation to perform the measurements was granted by the Ethics Committee at the Medical Faculty of the Eberhard-Karls University and the University Hospital Tübingen with ID 482/2021BO2.

All data was pseudo-anonymised and stored in full compliance with the Data Protection Act GDPR 2016/679 of the European Union.

2.2 Subjects & Informed Consent

A total of ten (10) volunteers (5 males/ 5 females) participated in the course of the study. Participants were aged between 20 and 25 years (mean = 22,8; SD= 1,69). None of the subjects presented a prior history of problems using a virtual reality headset or dry eye symptomatology.

Furthermore, the participants fulfilled the following inclusion criteria:

- Ability to communicate with the examiner and understand and sign informed content
- No previous eye disease or surgery
- No prior diagnose of dry eye
- No suffering from diabetes, gout, Sjögren's syndrome, arthritis, vitamin A deficiency
- Not pregnant
- Not regularly smoking
- Refractive error up to ±6.00 diopters
- Not wearing contact lenses
- No accommodative problems or problems with convergence
- No suffering from epilepsy, dementia or any neurological condition that makes safe use of the VR headset impossible

It also had to be ensured that participants do not participate in one or more clinical trials in parallel. Due to the tests to be performed, it was also impossible for persons with a fluorescein allergy to participate.

In order to check the subjects' eligibility, a questionnaire was sent to the potential participants in advance. This form included the standard OSDI (Ocular Surface Disease Index), and the additional participation criteria listed above. The OSDI is a reliable tool to measure dry eye disease's severity measured by vision-related function, ocular symptoms, and environmental triggers (42). This questionnaire was evaluated, and based on the results, the participants were invited for a first examination.

In this first examination, the experiment was explained in detail to the participants, and written informed consent was granted by each participant.

2.3 Materials

2.3.1 OSDI Questionnaire

The Ocular Surface Disease Index test (OSDI) is a questionnaire aiming to detect dry eyes. It contains twelve questions about the frequency of issues in three categories: the frequency of ocular symptoms like light sensitivity, gritty sensation, and vision-related functions. A daily life category, asking about difficulties while reading, driving, etc. And third, a category about potential environmental triggers and problems occurring, for example, in air-conditioned rooms. Every question was answered between 0 (never) to 4 (all the time). After these 12 questions are answered, they get an OSDI score between 0 and 100 (43). The OSDI Questionnaire is known as the best-validated questionnaire. Still, it cannot diagnose dry eye disease on its own, but it can be used to support the diagnosis (44). The OSDI score is also related to the severity of dry eye disease, even though the disease is slightly less severe than assessed with the OSDI-Questionnaire (42).

The OSDI-Questionnaire detects especially dry eye disease with an aqueous layer deficiency. There is also an inverse correlation between the tear film meniscus and the OSDI-Score) (45).

Only subjects with an OSDI score lower than twenty-five were included in this study.

2.3.2 Digital lensmeter

The digital lensmeter used is the Visulens 500 (Carl Zeiss Vision GmbH, Aalen, Germany). It is an automated lensmeter that can determine the refractive power. The measuring range of the sphere power is from -25 dpt to +25 dpt, of cylinder power ±10 dpt. The measuring wavelength is 546 nm.

The lens is placed in the device and fixed with the front side facing upwards. With the help of a cross on the device's screen, the optical center can be determined, and the dioptric value of the lens is obtained. If the subject is using glasses, it is possible to measure them to check if they are approximately the same dioptres as the subjective refraction to ensure their refractive error is corrected as well as possible.

2.3.3 Wavefront aberrometer

Wavefront aberrometry, in this case, is used to provide objective refraction and to acknowledge the refractive error of our subjects. The wavefront aberrometer used was the iProfiler plus (Carl Zeiss Vision GmbH, Aalen, Germany). This device combines a Hartmann-Shack wavefront aberrometer, autorefractometer and keratograph. First, the device is placed at the subjects' height so they can comfortably place their head on the chin rest. The forehead must be leaned against the top during the measurement. During the measurement, the

participant must gaze at a fixation target in a hot air balloon shape. During the measurement, the balloon becomes blurred, but the participant should still look at it in a relaxed manner. Based on the objective refractive error measured with this device, subjects with a refractive error of up to ±6.00 diopters were included.

2.3.4 Swept-source optical coherence tomography

The IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) uses swept-source technology to determine the eyes' biometric data. It measures the axial length of the eye, the anterior chamber depth, lens thickness and central cornea thickness (46). It is usually used to determine the power of an IOL (intraocular lens), e.g. in cases of cataract. Swept-source OCT belongs to the Fourier domain OCTs, using a tunable laser source, which can use the same spectrum as a wideband source in time-domain-OCTS (47,48).

In this study, the IOLMaster was used to measure the eyes' length as part of the standard operating procedure in the lab. The subjects need to put the chin on the chinrest, lean the forehead on the top and gaze straight while the operator performs the measurements.

2.3.5 Optical coherence tomography

Optical coherence tomography is a non-invasive procedure using low-coherence interferometry to create a two-dimensional image of intern structures similar to ultrasound (49). It is typically used to picture the eye's inner structures in ophthalmology.

The used OCT was the Zeiss Cirrus™ AS-OCT (Carl Zeiss Meditec AG, Jena, Germany). Like in the other devices, the subjects had to place their heads in the chin rest and lean their foreheads against the top. Then they need to fixate at a specified point in the device. The examiner would adjust the measuring point and measure the tear film meniscus using the anterior segment additional lens. Turning off the lights can improve the quality of the recordings.

The height and the depth of the meniscus tear film can be measured using the ruler tool within the device software as shown in Figure 2.
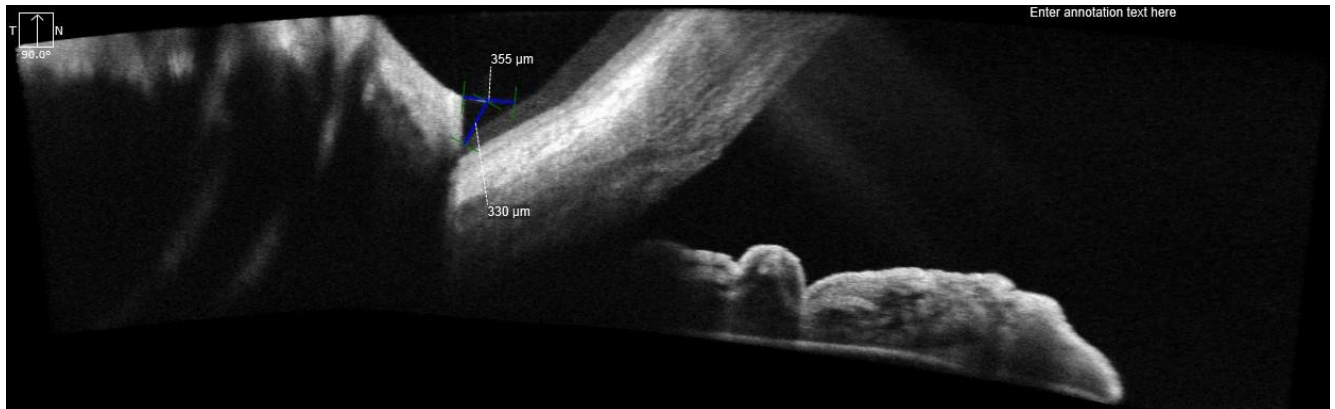
Figure 2 OCT image of the tear meniscus, height and depth measured with the ruler tool from the devices software

2.3.6 Slit lamp

The slit lamp (ZEISS SL 120, Carl Zeiss Meditec AG, Jena, Germany) was used for the binocular examination of the eyes of the subject. Slit width and length are adjustable. Several types of illumination can be used, depending on what needs to be seen. In our case, diffuse illumination, direct focal illumination, and indirect illumination were combined with different magnifications.

The subject sits in front of the device, places his head on the chin rest and leans his forehead against the top. The chin rest can be adjusted in height to be comfortable for the subject, and the examiner can examine it without any problems. For the examinations, it is helpful if the subject fixates on a point in the background. For the general examination, the examiner scans the important areas of the eye, including the eyelids, conjunctiva, and cornea. Depending on the area being examined, a different type of illumination is selected. If there are abnormalities, these can be viewed under higher magnification. To examine with fluorescein, the light colour must be switched to blue.

2.3.7 Schirmer strip tests

The Schirmer test (Schirmer Tear Test, Optitech Eyecare, Prayagraj, India) is one of the most widely used ways to measure the tear film quantity. It is possible to perform this test with and without local anaesthesia. Without anaesthesia, subjects are supposed to keep their eyes closed, as seen in Figure 3, since the results are more reliable (50). The Schirmer strips are inserted into the lower eyelid, the subject is asked to close the eyes, and the strips become saturated with fluid. Contact of the strip with the cornea is avoided here by inserting the strip as temporally as possible. With normal tear film production and measurement without anaesthesia, the measurement value is above5 to 10 mm after 5 minutes. No definite limit can be found for normal tear production (51). The test is invasive, and most patients find it irritating; though the test becomes less uncomfortable the more often it is performed on one subject (52). It is not supposed to be used for diagnosing

dry eye on its own since there is a high risk of underdiagnosis (50). Instead, it is used to support the diagnose of dry eye.

Figure 3 Subject getting a Schirmer test done

2.3.8 Fluorescein stripes

Fluorescein sodium is one of the most common vital dyes used to stain ocular surface damage. It is an orange dye dissolved in water that fluoresces green when stimulated by blue light (53). The Fluorescein stripes (Fluorescein Sodium Ophthalmic Strips, Care Group, Vadodara, India) were used to stain corneal and conjunctival cells in cases of damage and to perform the tear film break up time measurement. These stripes are made of filter paper containing fluorescein in the tip. The tip of the strip gets moistened with saline solution before applying the fluorescein to the eye. After the application, the subject is supposed to blink to spread the fluorescein homogeneously.

2.3.9 CE approved virtual reality headset

A VR headset is a screen that is attached to the head close to the eyes. Sensors detect the position of the headset and movements. Thanks to the stereopsis, a virtual environment presented on the screens create a three-dimensional image in the brain. The used headset (Fove 0, Fove Inc, Torrance, CA, USA) includes video feedback from the eye, which allows us to measure the blink rate afterwards. It uses an OLED-Display with a frame rate of 70fps and Fresnel lenses. A Microsoft Xbox controller was additionally used for input while the subjects played.

2.3.10 Raspberry Pi computer board with Temperature and humidity sensor and O2 sensor

Raspberry Pi computer board (Pi Foundation, UK) was used in combination with a temperature and humidity sensor (Sensirion SHT21) as well as an O2 sensor (Grove Gas Sensor(O2), ME-02-D20) to track temperature, humidity and O2 in the periocular environment of the VR Headset while playing, as well as during playing with a normal desktop. The data was recorded every ten seconds. The temperature and humidity sensor has an operating relative humidity range from 0% to 100% and an operating temperature range from -40°C to 125°C. The relative humidity accuracy is 2%, and the temperature accuracy is 0,3°C (54). The oxygen sensor can measure oxygen concentration within a range from 0% to 25%, while the maximal detecting concentration lies at 30%. The sensor's repeatability is <2% (55). Since the oxygen sensor needs to preheat 20 minutes before usage, the Raspberry Pi and the sensor were started 20 minutes before measuring.

2.3.11 Eye-tracking device

The device (Pupil Core, Pupil Labs, Berlin, Germany) is a wearable eye-tracking headset with cameras to record what is seen by the subject and their eyes position. It records the eyes' movements and can additionally measure the blinking rates reliably. In our study, it was used whilst working with a typical computer desktop (56). The device is also easily adjustable if the subject wears glasses and is lightweight, thanks to the PA12 Nylon it is made of.

2.3.12 Computer Working station

The desktop workstation consisted of a computer, screen, keyboard, and mouse used for different things. The game platform for the VR headsets and traditional desktop ran on this computer, as did the software for the eye-tracking device.

2.4 Methods

This study aimed to evaluate the effect of virtual reality head-mounted displays over the tear film compared to traditional office environments. The experiment itself was divided into three parts, explained in the following sections. The first session consisted of a pre-examination to ensure the subjects fulfilled all the inclusion criteria. During the second and third parts of the experiment, subjects played with a HMD or a Desktop, and their tear film was measured and evaluated afterwards.

2.4.1 Assessment methods

Different assessment methods were used to analyse the tear film and health of the eyes of the subject in addition to the Schirmer test.

2.4.1.1 Efron Grading Scale

A grading scale is used to quantify the severity of a condition, comparing standardised pictures to the current state. The Efron grading scale is usually used to grade contact lens complications. It has five different levels of severity where "0" is normal, and "4" is severe. Different grading scales are available, so it is important to use the same consistently once one is chosen (57). A change of one grade or more may be clinically as well as statistically significant (58). The categories used for this study were corneal infiltrates, corneal staining, limbal redness and conjunctival redness.

2.4.1.2 Tear film Break-up Time

The tear film break-up time (short TBUT) helps measure the tear film stability. A small amount of fluorescein is given to the ocular surface. While looking through the slit lamp, the subject is asked to blink once. Then the subject is supposed to leave the eyes open until dry spots are visible or cannot withstand a blink. The seconds from the blink until the appearance is the break-up time. A break-up time bigger than 10 s is considered normal. The fluorescein is supposed to be given without topical anaesthesia to measure the TBUT (50).

2.4.2 Pre-measurements

The preliminary measurements ensured that the subjects met the minimum requirements. Here, the subjects were first informed about the study procedure. Then they needed to sign the declaration of consent to the handling of the data collected in the study and the declaration of informed consent for participation in the study. Afterwards - if available - the glasses were measured with a lensmeter. Then, both eyes of the participants were measured with an autorefractometer. Another examination was performed with the Zeiss IOL Master, where the eye length was determined.

The last two measurements on devices were performed with an OCT, obtaining a standard image of the ocular fundus and a section of the anterior segment of the eye, on which the lacrimal meniscus can be seen.

Finally, an examination with a slit lamp followed, in which the eye was examined and compared with the Efron Grading Scale for four different categories. The four categories were corneal infiltrates, corneal and conjunctival staining and limbal redness.

A Schirmer test was also performed bilaterally, and the tear film break-up time (TBUT) was measured after applying fluorescein.

2.4.3 Experiment part one

In the first part of the experiment, the subject played a game with HMD glasses for 90 minutes.

During this time, the eye movements and thus the blinks were tracked with the glasses. In parallel, a Raspberry Pi, mounted as shown in Figure 4, measured oxygen, temperature, and humidity at intervals of ten seconds. The O2-sensor was connected to the headset inside area through a plastic tube, given that the sensor was too big to be placed inside the headset. The Temperature-/Humidity-sensor was put between the foam and the headset to measure on the inside.
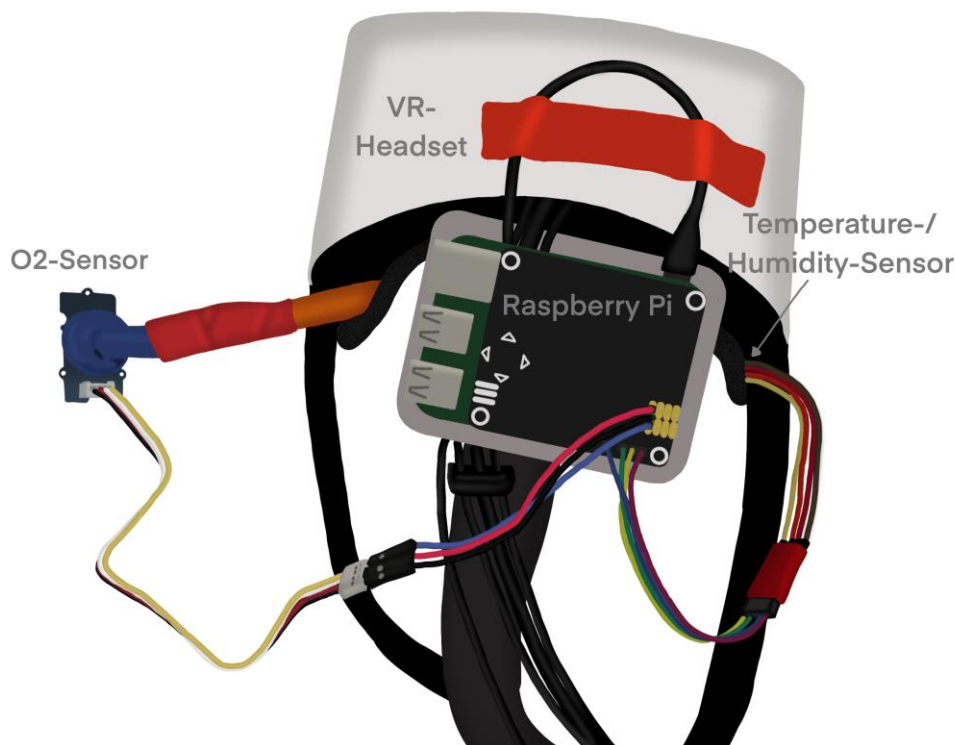

Figure 4 HMD-Headset with O2-Sensor and Temperature-/Humidity-sensor and a Raspberry Pi mounted on top

The subject sat in front of the PC while playing, freely moving in the range of the cables and tracking area, as shown in Figure 5, and input for the game was given through an controller. The headset was connected to the computer via HDMI and USB.

Figure 5 Subject playing HMD

Following gaming, a picture of the tear meniscus was taken with the OCT. The eye was again examined with the slit lamp, and the Efron grading scale was applied to the four categories mentioned above. Afterwards, the Schirmer test was again performed bilaterally, followed by a measurement of TBUT using fluorescein.

2.4.4 Experiment part two

The second part of the experiment was similar in structure to the first part. 90 minutes were played on the PC screen, while the eyelid blink frequency was measured with the help of an eye-tracking device. The sensors controlled by the Raspberry Pi were attached to the device, as shown in Figure 6, for recording temperature, humidity, and oxygen every ten seconds.
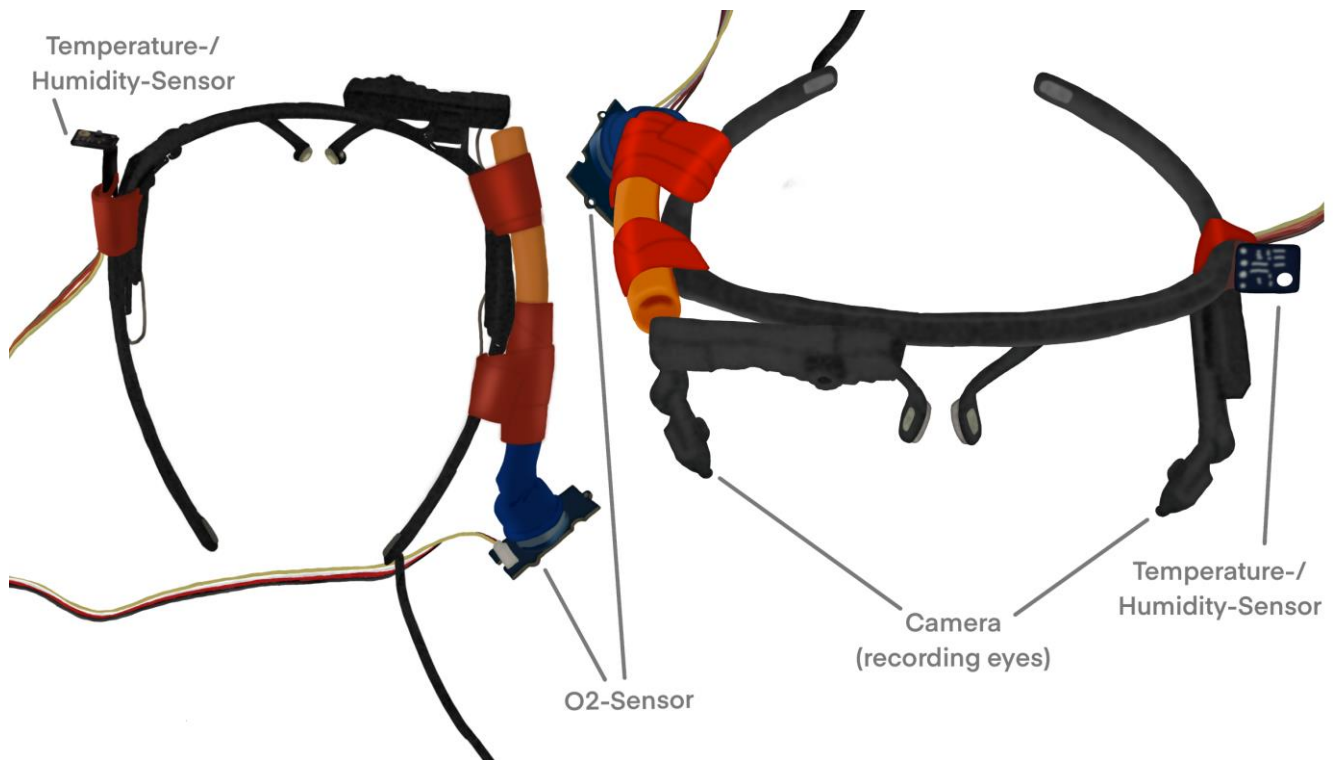
Figure 6 Eye tracking device from above and frontal, with O2-Sensor and Temperature-/Humidity-Sensor

If the subjects were wearing spectacles, they could be worn over the eye-tracking glasses, as shown in Figure 7.

Figure 7 Subject playing on the computer while wearing an eye-tracking device

This was followed by imaging the tear meniscus using the OCT and slit-lamp examination.

The same four categories (limbal and conjunctival redness, corneal staining, corneal infiltrates) were graded according to the Efron grading scale, followed by the Schirmer test. As a final examination, TBUT was measured after applying fluorescein. The measurement flow is shown in Figure 8.
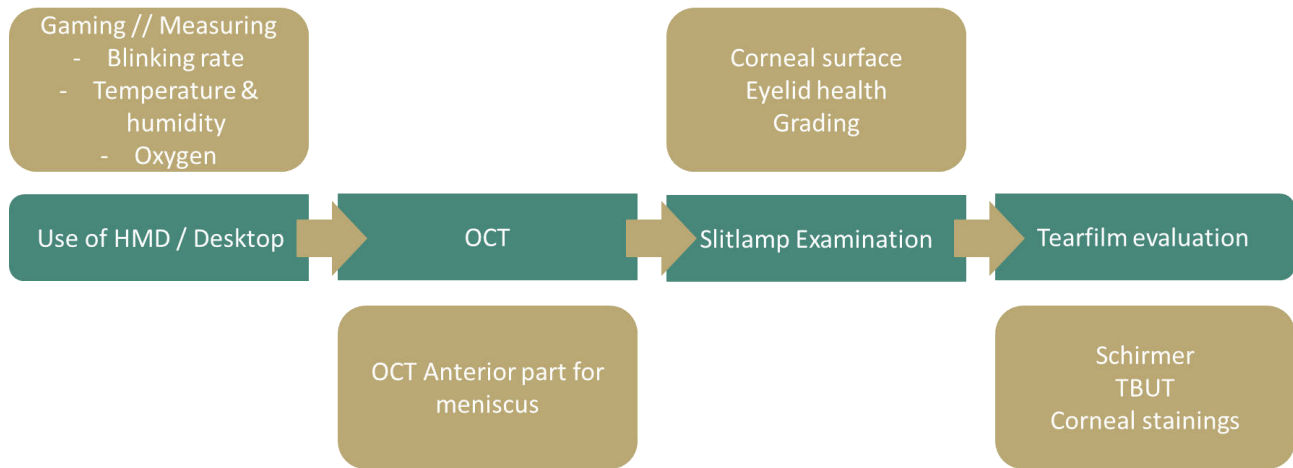

Figure 8 Measurement procedure

3 Results

Statistical analysis was performed using MATLAB (MATLAB 2021b, The MathWorks, USA) and its Statistics Toolbox. Since no normal distribution was found using the one-sample Kolmogorov-Smirnov test, non-parametric tests were used.

The total number of subjects was n = 10 (5 males, 5 females) with a mean age of 22,8 (SD = 1,69) and a mean OSDI score of 6,46 (SD = 7,27).

3.1 Efron grading scale

To compare the grades from the baseline measurements, the measurements after using an HMD and the measurements after usage of a conventional screen, a non-parametric Kruskal-Wallis test was performed.

No statistically significant difference was found in conjunctival infiltrates (H(2) = 2,0; p = 0,1227), neither in corneal staining (H(2) = 3,41; p = 0,1821), nor in conjunctival redness (H(2) = 3,04; p = 0,2192) or in limbal redness (H(2) = 3,9; p = 0,1425).

3.2 Schirmer test

Since the Schirmer test first applied had a higher value than the Schirmer test performed on the second eye (mean OD = 27,9 mm; mean OS = 20,1 mm), possibly due to a tear reflex, only the Schirmer tests on the left eye were analysed. A non-parametric Kruskal-Wallis test was performed to compare the results from the baseline measurements, the HMD measurements, and the measurements after usage of a PC Screen.

There were no statistically significant differences between the baseline Schirmer test results and the Schirmer test results after playing with an HMD or on a conventional screen (H(2) = 4,2; p = 0,1227).

The mean of the Schirmer test before all measurements was 20,1 mm (SD = 9,4 mm), and the mean of the Schirmer test after playing with an HMD for 90 minutes was 12,5 mm (SD = 10,9 mm). After playing on a conventional screen for 90 minutes, the mean of the Schirmer test was 11,6 mm (SD = 5,5 mm). The Schirmer test results compared for each subject are shown in Figure 9.
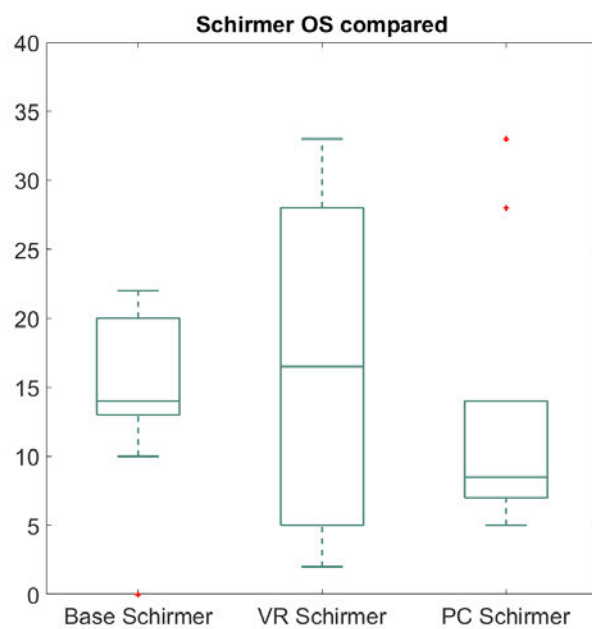
Figure 9 Schirmer test results compared for each subject

3.3 TBUT

The TBUT baseline measurements were compared against the HMD and the PC screen measurements using the non-parametric test equivalent to ANOVA, Kruskal-Wallis.

The mean of the TBUT baseline measurements is 17,3 s (SD = 4,69 s), and the mean TBUT after playing with an HMD for 90 minutes is 12,7 s (SD = 5,23 s). After playing on a conventional screen for 90 minutes, the mean TBUT is 9,6 s (SD = 5,25 s).

Using the Kruskal-Wallis test, a statistically significant difference was found (H(2) = 8,35; p = 0,0154). Post hoc comparisons using the Tukey-Kramer test found statistically significant difference between the baseline TBUT results and the TBUT results after playing on a conventional screen (p = 0,012), which is shown in Figure 10 by the line connecting the two different groups. No statistically significant difference was found between one of those and the results after playing with an HMD, even though a slight difference between them is visible in Figure 10.
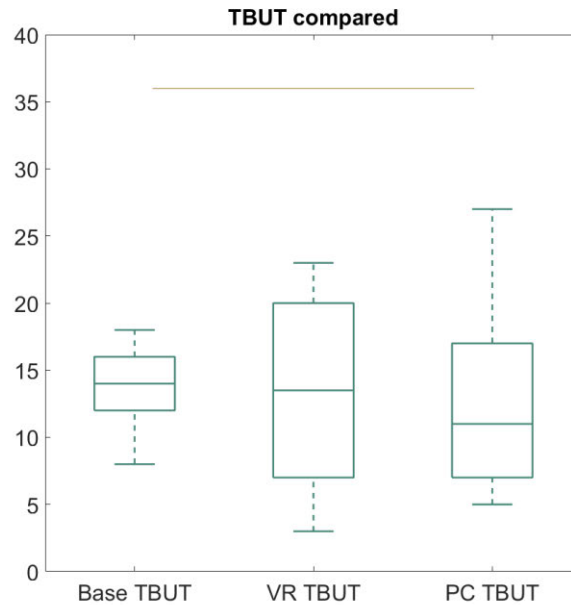
Figure 10 Kruskal-Wallis test comparing TBUT

3.4 Meniscus

Data Analysis of the OCT meniscus images was done on the OCT itself. The height and depth of the meniscus were measured using the ruler tool within the device software. Then, the baseline, HMD and PC measurements were compared using the Kruskal-Wallis-test.

3.4.1 Meniscus height

The mean of the baseline heights was 260,0 µm (SD =102,45 µm) on the subjects' right eye and 226,9 µm (SD = 88,44 µm) on the left. The mean height after playing with an HMD for 90 minutes was 232,7 µm (SD = 81,16 µm) on the subjects' right eye and 233,9 µm (SD = 62,82 µm) on the left. After playing on a conventional screen for 90 minutes, the mean height was 252,8 µm (SD = 86,99 µm) on the subjects' right eye and 237,1 µm (SD = 70,24 µm) on the left.

On neither of the sides statistically significant difference was found between the baseline heights and the meniscus heights after playing on a conventional screen nor the heights after playing with an HMD (OD: (H(2) = 0,39; p = 0,8228; OS: H(2) = 1,27; p = 0,5304).

3.4.2 Meniscus depth

The mean of the baseline depths was 163,4 µm (SD = 38,32 µm) on the subjects' right eye and 138,8 µm (SD = 29,18 µm) on the left. The mean depth after playing with an HMD for 90 minutes was

159,8 µm (SD = 45,85 µm) on the subjects' right eye and 144,9 µm(SD = 43,44 µm) on the left. After playing on a conventional screen for 90 minutes, the mean depth was 165,8 µm(SD = 36,80 µm) on the subjects' right eye and 164,0 µm(SD = 44,42 µm) on the left.

No statistically significant difference could be found in the meniscus depths between any of the measurements (OD: (H(2) = 2,73; p = 0,9654; OS: H(2) = 1,99; p = 0,3706).

3.5 Sensors

The sensors' measurements of temperature, oxygen and humidity every ten seconds were visualised in a diagram. Then the mean values were calculated with MATLAB and plotted. A Mann-Whitney-U-test was performed to determine if there was a significant difference between the measurements during playing HMD or while playing on a conventional screen.

A non-parametric Kruskal-Wallis test was performed to compare the different time intervals (from 0 minutes to 30 minutes, >30 minutes to 60 minutes and >60 minutes to 90 minutes). The temperatures, oxygen levels and humidity means and standard deviations of the different time intervals can be found in Table 1. In this table, the differences between the usage of an HMD and a conventional screen are already visible but will be explained in the following subsections.

Table 1 Means and standard deviations of temperature, oxygen, and humidity, divided into three time intervals of 30 minutes each, for HMD and conventional desktop usage

		0 - 30 min	>30 - 60 min	>60 - 90 min
Temperature HMD	**mean**	32,18	33,41	33,61
	SD	1,06	0,11	0,04
Temperature PC	**mean**	25,38	25,71	25,86
	SD	0,14	0,08	0,07
Oxygen HMD	**mean**	14,14	14,06	14,08
	SD	0,14	0,02	0,05
Oxygen PC	**mean**	16,12	16,14	16,14
	SD	0,03	0,01	0,02
Humidity HMD	**mean**	81,19	82,13	79,93
	SD	2,19	0,57	1,27
Humidity PC	**mean**	29,75	28,76	27,60
	SD	0,84	0,78	0,48

3.5.1 Temperature

As seen in Figure 11, the VR-Headset (green) temperature rises the most during the first 30 minutes and then remains constant. The temperature measured during playing on a conventional screen (yellow) remained lower at all times.
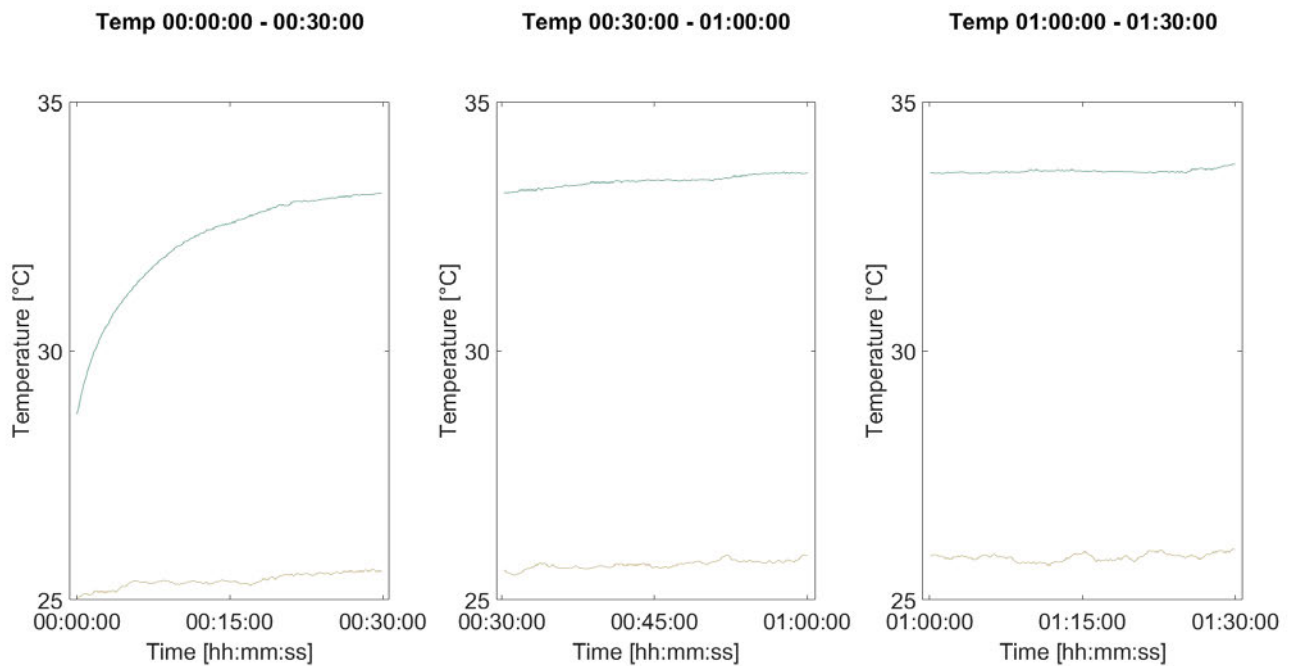

Figure 11 Temperature over time (green: HMD, yellow: conventional screen)

There was a statistically significant difference in temperature between VR and PC (Mann-Whitney-U, $Z = -28,4484$; $p < 0,01$) during the whole sessions. To further compare the different time intervals, a non-parametric Kruskal-Wallis test was used.

A statistically significant difference was found between each of the intervals while playing with an HMD ($H(2) = 463,26$; $p < 0,01$) and while playing on a conventional screen ($H(2) = 425,99$; $p < 0,01$).

3.5.2 Oxygen

In Figure 12, the mean oxygen levels of all subjects while playing with an HMD (green) and playing on a conventional screen (yellow) are shown over the time of 90 minutes. The time is divided into thirds. In the first third, the VR headset's oxygen level decreases, but afterwards, it remains stable. The oxygen level measured while playing on a conventional screen remains stable over the whole 90 minutes.
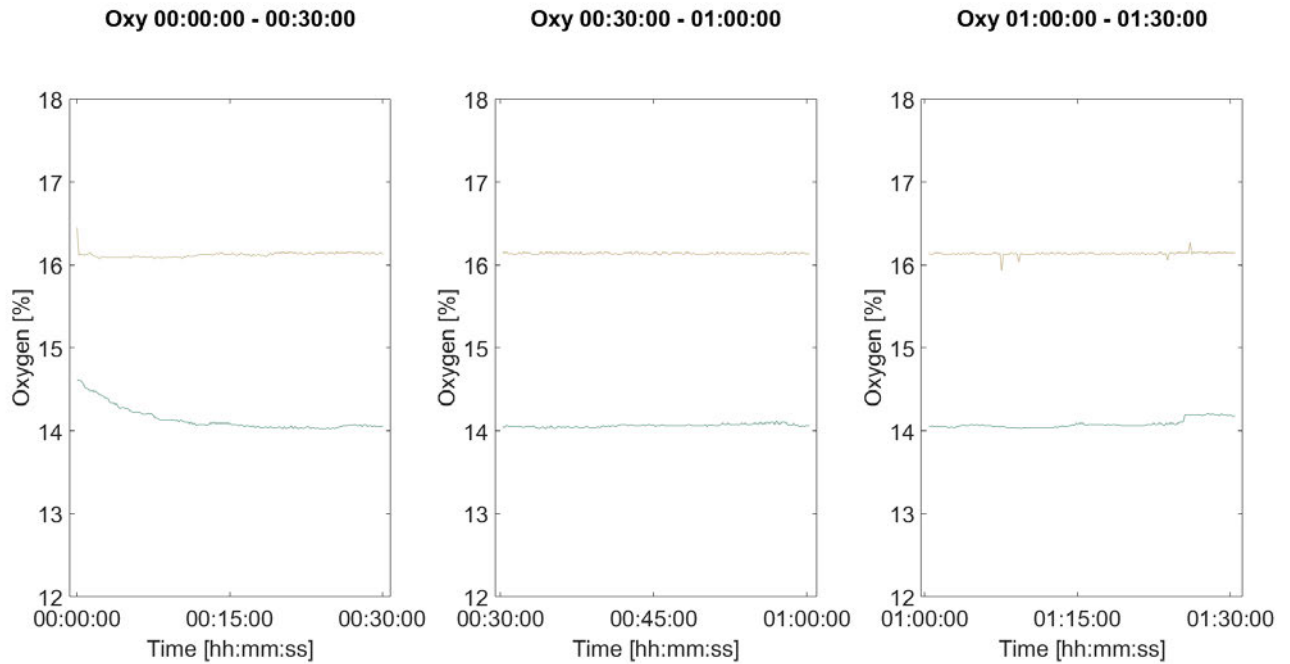
Figure 12 Oxygen levels over time (green: HMD, yellow: conventional screen)

A Mann-Whitney-U-Test was performed to determine differences in the oxygen levels between playing with an HMD and playing on a conventional screen. A significant difference was found in oxygen levels between both groups (Z = -28,6676; p < 0,01).

A non-parametric Kruskal-Wallis test was used to compare the oxygen levels in the different time intervals(H(2) = 11,04; p < 0,01).

Performing a Tukey-Kramer test, a statistically significant difference was found between the first interval and the second (p = 0,0052) and third interval (p = 0,0287) of oxygen levels while playing with an HMD No statistically significant difference was found between the second and the third interval in oxygen levels whilst playing with an HMD.

Whilst playing on a conventional screen, only a statistically significant difference was found between the first interval and the second and third (H(2) = 54,91; p < 0,01).

3.5.3 Humidity

Whilst playing with an HMD, the humidity increased in the first thirty minutes, but it decreased in the last thirty minutes, as shown in Figure 13 (green line). Meanwhile, the humidity while playing on a conventional screen (yellow) stayed stable and was lower.
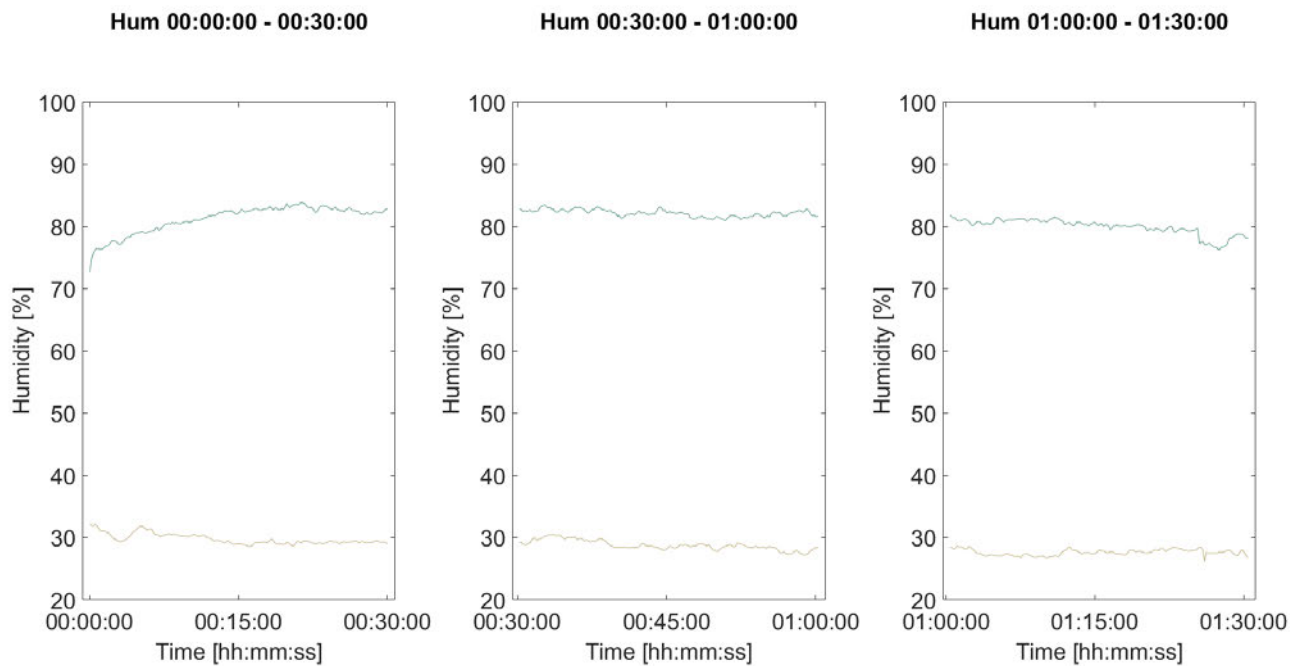

Figure 13 Humidity over time (green: HMD, yellow: conventional screen)

A Mann-Whitney-U-test was performed to determine differences in humidity levels around the eye while playing with an HMD and playing on a conventional screen. There was a statistically significant difference in oxygen levels between both groups (Z = 28,4473; p < 0,01).

For comparing the humidity depending on the time intervals, a non-parametric Kruskal-Wallis test was performed. A statistically significant difference was found between all three-time intervals while playing with an HMD (H(2) = 201,67; p < 0,01). Similarly, when playing on a conventional screen, a statistically significant difference was found between all intervals (H(2) = 353,59; p < 0,01).

3.6 Blinks PC

To compare the amount and duration of blinks in different time intervals, the means were calculated by MATLAB. Those were compared by a non-parametric Kruskal-Wallis test.

3.6.1 Blink frequency

Every blink was recorded by an eye tracking device. As observed from the data cluster in ten min intervals and plotted in Figure 14, there is no clear tendency for a change in the blinking frequency over time.
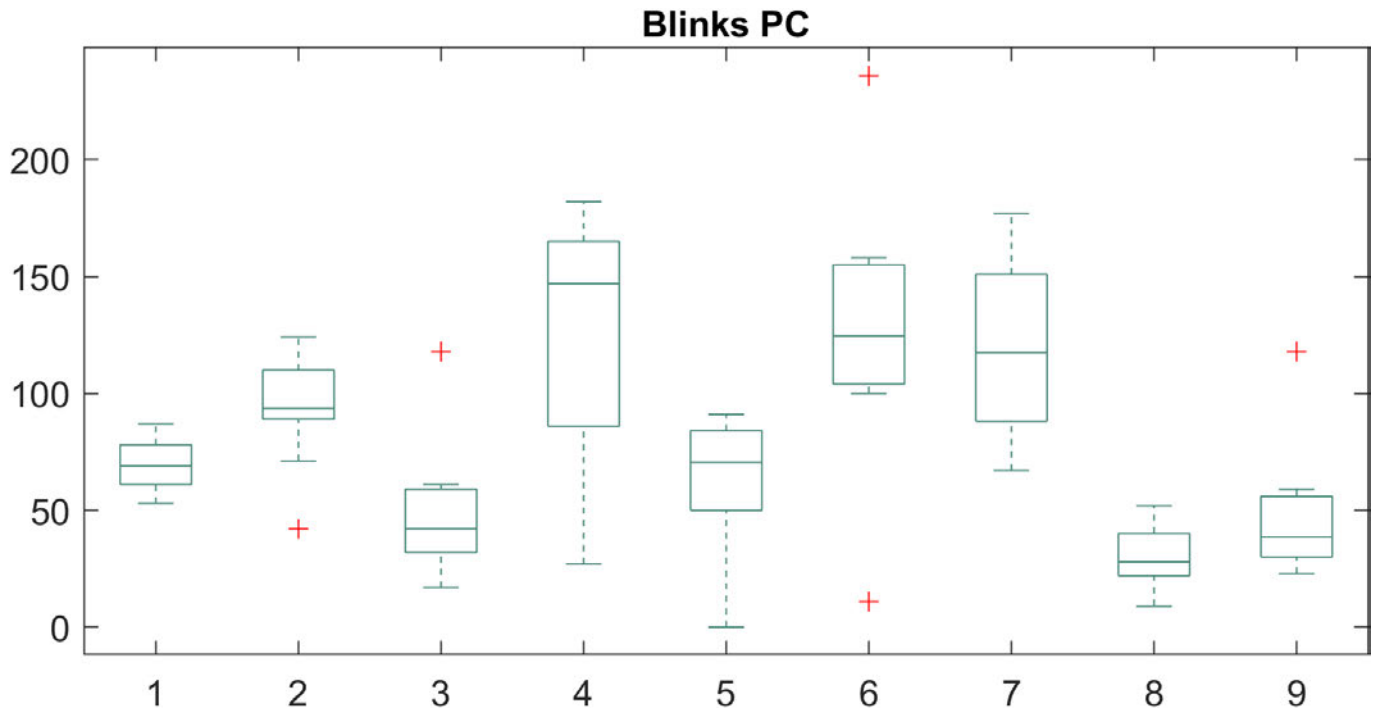
Figure 14 Boxplot of the amount of blinks in nine time intervals, each 10 minutes long, while playing on a conventional screen

A Kruskal-Wallis test was performed to compare the number of blinks in thirty-minute time intervals.

No statistically significant differences were found between the number of blinks in all three time intervals while playing on a conventional screen (H(2) = 2; p = 0,2679).

3.6.2 Blink duration

The device recording the blinks also recorded the blink duration. For nine intervals, each ten minutes long, the means of the blink duration of each subject were calculated. As shown in Figure 15, there is no clear tendency of the blink duration over the course of 90 minutes.

Blinks PC

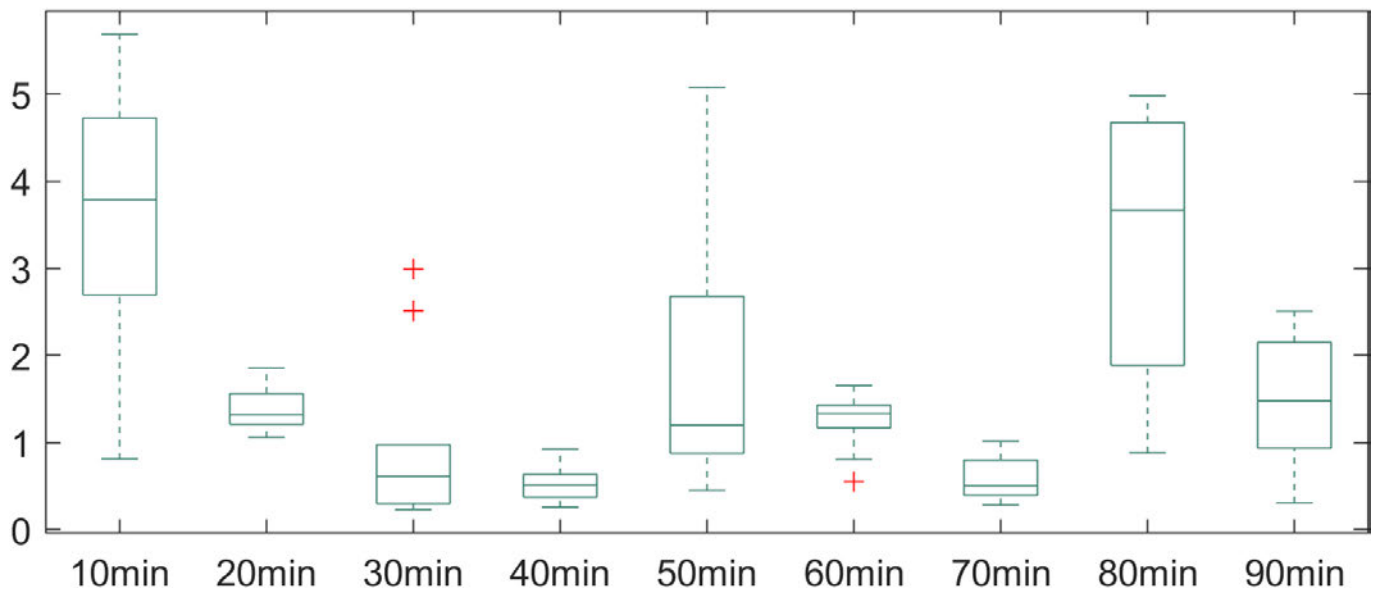*Figure 15 Boxplot of the blink duration of each subject in nine time intervals, each 10 minutes long while playing on a conventional screen*

To compare the blink duration in thirty minute intervals, a Kruskal-Wallis test was performed.

No statistically significant difference was found between the blink duration in all three time intervals while playing on a conventional screen (H(2) = 2; p = 0,3679).

4 Discussion

The study analysed how differently it can affect the tear film, working with an HMD and with a conventional screen, by comparing the different measurements taken after ninety minutes of using these.

After analysing the tear film, no statistically significant differences were found between the usage of conventional screens and HMDs, even though a slight tendency is visible, showing that the Schirmer test and TBUT results are better after HMD usage.

No statistically significant differences were found in any of the chosen Efron grading scales between the grades from the baseline measurements, the measurements after HDM usage or the measurements after using a conventional screen.

The Schirmer test results compared, the mean before playing is clearly higher than the means after using an HMD and after conventional screen usage, even though no significant difference was found. Comparing the TBUTs, only a significant difference was found between the measurements before playing and after the usage of a conventional screen. The mean of the TBUT after usage of an HMD is between the both of them and slightly better than after playing on a conventional screen. No differences were found in the tear film meniscus between conditions (Baseline vs PC vs VR), and the meniscus means heights and depths were quite similar before playing and after using an HMD and a conventional screen.

However, the results sensors measuring temperature, humidity, and oxygen inside the headset and outside while using a conventional screen show some significant differences in all categories. Oxygen levels are lower in the headset, with the temperature and humidity rising in the first 30 minutes of playing and staying mostly stable then. However, these parameters do not seem to change as much while playing on a conventional screen.

No clear tendency can be found during the period of 90 minutes, neither were significant differences found in the blinks or blinks durations.

4.1 Literature discussion

When all measurements were completed, subjects were asked what they had found more comfortable for the eyes, and eight out of ten chose the HMD. Yoon et al. (2021) found that subjects did have more subjective dry eye symptoms after playing with an HMD for two hours compared to two hours of smartphone usage (40), whereas Marshev et al. found no significant difference in fatigue and discomfort after 20 minutes of usage of an HMD and a conventional screen. Outside temperature and humidity were controlled by air conditioning, but those measurements have not been taken inside the VR headset to compare. (39). The subjective feeling of dryness whilst playing with an HMD and after could also be camouflaged by the high humidity found in the headset and the missing airflow since a lower humidity would have increased the evaporative rate (59).

The high temperature while playing with an HMD and the lower oxygen levels could worsen the quality of the tear film. Mendell et al. found in 2002 that increasing temperature also increases the severity of dry eye symptoms (60).

Measuring for a longer time than Turnbull et al., the increased tear film stability could not be replicated in our study, as they found after playing for 40 minutes. We measured temperature more often than every five minutes and can support the findings of an increase in the temperature inside the HMD. Nevertheless, our humidity findings do not coincide with the ones reported by Turnbull et al. Their humidity while using an HMD decreased while ours did increase especially in the first 30 minutes. The differences in humidity inside and outside the devices might be reasons for the differences in results regarding the impact of HMDs on the tear film (41).

4.2 Limitation/critics

The findings of this study might have been influenced by several limitations of the study, like the duration of the sessions and the number of subjects measured. A negative point may also be that not the same or similar games were played both times, which may have led to different levels of attention and concentration among the subjects. However, there are not many games available that can run well both in VR and on a traditional desktop.

When playing with the HMD, many subjects presented problems of nausea and cybersickness, which is why a large part of the initially targeted subjects could not be included in this study. Motion sickness occurred in most cases after 20 to 30 minutes. Unfortunately, this is not an entirely unknown problem with VR headsets (61) but could possibly be improved by using a different device in which more adjustable parameters, such as pupil distance and better tracking of the headset.

Additionally, due to Covid-19, the subjects had to wear a mask for protection throughout the experiment. However, if the mask does sit not tight enough on the cheeks and nose, the exhaled air escapes upwards towards the eyes. This, in turn, supports the tear film's evaporation and dries the eyes faster (61). Since all subjects were students with remote learning, some of them might have spent some time in front of the screen before the measurements were taken. To avoid the different initial situations for all three parts of the measurement, these took place at similar daytimes. However, it could not be ensured that they have spent similar times on screen these days.

Another problem occurring was data corruption of the measurements of oxygen. Thus, not all results of subjects measured after 90 minutes of playing could be used in this study. Finally, to compare blink frequency and the blinks' duration between the usage of both devices, a thorough evaluation of the data from the VR headset is needed. However, due to the camera position in the device, which is quite low, it did not capture both eyes completely, leaving the analysis of it out of the scope for this thesis.

Additionally, further measurements could be taken to improve the overall design of the study. Before measuring the TBUT, the NIBUT could be measured with a keratograph or similar since it is a non-invasive method, and no additional fluid is given to the eye in the form of saline solution to apply fluorescein. Moreover, a keratograph or similar offers the possibility to analyse and compare the tear film lipid layer.

In any case, what was striking in this study were the significant differences in oxygen levels, temperature, and humidity between the use of an HMD and the use of a conventional screen, but also the increase in temperature and humidity and the drop in oxygen in the first 30 minutes of HMD use. The subjective feeling of HMD being more comfortable for the eyes than a conventional screen, which eight out of ten subjects reported in this study, should also not be lost sight of in future measurements.

5 Conclusion and Outlook

No significant difference in the effects on the tear film between the use of HMDs and conventional screens could be found; only the differences in the surrounding factors such as humidity, temperature and oxygen provide information about how they could have affected the tear film differently. A slightly better effect can nevertheless be taken from the figures. For practical purposes, it is necessary to continue the study with more participants to gain clearer insights. A comparison of other parameters, such as blink frequency, would also be useful to draw a final conclusion. With the further development of HMDs and more widespread use, it would be important to know about the effects of these devices on the tear film and associated symptoms.

In the future, in addition to conducting with a higher number of participants, the time dependency of changes should be examined to gain insight regarding an adequate duration for their usage. Furthermore, measurements regarding the rebound effect due to possible masking of the dry eye symptoms by high humidity and temperature in the headset cannot be discarded.

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Declaration

I declare that this thesis, which I submit to Aalen University for examination in consideration of the award of a higher degree B.Sc. (Optometry) is my own personal effort. Where any of the content presented is the result of input or data from a related collaborative research program this is duly acknowledged in the text such that it is possible to ascertain how much of the work is my own. I have not already obtained a degree at Aalen University or elsewhere based on this work. Furthermore, I took reasonable care to ensure that the work is original, and, to the best of my knowledge, does not breach copyright law, and has not been taken from other sources except where such work has been cited and acknowledged within the text.

Signed ___██████████████████_____

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Date ___Tübingen, 31.03.2022_____