COMPUTER VISION SYNDROME IN HEAD-MOUNTED DISPLAYS: SPONTANEOUS EYE BLINKS AND SACCADES

by

Noah Bannister

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STATEMENT OF COMMITTEE APPROVAL

Dr. David Whittinghill, Chair

Department of Computer Graphics Technology

Dr. Tim McGraw

Department of Computer Graphics Technology

Mr. George Takahashi

Envision Center Technical Lead

Approved by:

Dr. Nicoletta Adamo

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ABSTRACT

While computer vision syndrome has been meticulously studied in the context of desktop, laptop, and smart phone displays, there is a gap in the field when it comes to the effects of head mounted displays (HMDs). As the more consumer grade HMDs have become available, it has become important to understand visual strain symptoms associated with their use. This thesis has started to fill that gap by examining one of the known risk factors of dry eye in the context of head mounted display use. To do this, spontaneous eye blink rate was measured across head mounted display and real-world, direct viewing conditions. Head mounted display viewing allows more freedom of movement than desktop, laptop, or phone display viewing. Therefore, gaze shifts were examined to determine whether their corresponding blinks occurred with normal frequency during head-mounted display use.

The eye movements of seven participants were recorded as they shifted their gaze between two gaze targets in both direct viewing and virtual reality viewing conditions. Gaze targets were placed at different degrees of separation throughout the experiment. Backward elimination using ANOVAs and F-tests was used to identify significant predictors of blink rate, gaze evoked blinks, inter-blink period, and head rotation.

HMD use was found to have no significant effect on blink rate or gaze evoked blinks. Both main and interaction effects of HMD use were found to be significant for head rotation during gaze shifts. Inter-blink period was significantly affected by the interaction between HMD use and angle of separation between gaze targets. A case is made to show this was likely due to the experimental design.

CHAPTER 1. INTRODUCTION

Decades of observations have revealed that extended computer display use can temporarily affect the user's ocular function and comfort. Such ailments have been given the name computer vision syndrome (CVS), and are classified as repetitive strain disorders. Further, such effects have been shown to significantly affect perceived quality of life in workers who use computer displays (Hayes, Sheedy, Stelmack, & Heaney, 2007).

There are many specific symptoms classified as computer vision syndrome. This study has focused on one of the most common: dry eye. In the context of CVS, dry eye occurs when blinking does not replenish the protective tear layer as quickly as it breaks down. Reduced blink rates and wide palpebral apertures observed during computer use are the accepted causes of CVS dry eye.

Problem statement

While computer vision syndrome has been extensively studied with the use of desktop displays, it has yet to be studied with the use of head mounted displays (HMDs). With the expanding virtual reality market and increase in industry applications of the technology, it is important that these ergonomics studies be extended to head mounted display use. This study aims to begin this research by focusing on the relations between dry eye and blink, saccade, and gaze shift patterns during HMD use. Dry eye symptoms were not examined directly, but risk has been inferred through the study of spontaneous eye blink rate, a well-established risk factor.

Outside of head mounted displays, saccadic eye movements usually accompany head rotations when gaze shifts are made. Saccadic eye movements of sufficient magnitude are often accompanied by blinks. This led to the idea that saccadic eye movements may increase the spontaneous blink rate, implying the possibility that risk of dry eye when using an HMD may be less than when using a desktop monitor. That is, the greater and more frequent saccades possible when using HDMs may combat desiccation by promoting blinking. The link between gaze shifts and eye blinks had yet to be studied in head mounted displays, however. It was not a safe assumption that blinking is concurrent with gaze shifts during HMD use. It was considered that saccadic eye movements may be discouraged due to limited field of view and the discomfort caused by lens distortions and incorrect vergence projections when gaze is not directly forward. Therefore, smaller or less frequent saccades could reduce the compulsion to blink.

Scope

The primary goal of this research was to perform an ergonomics and eye health study on head mounted displays. Spontaneous eye blinks responsible for replenishing the protective tear layer were the primary focus of this study. The approach taken was based upon the correlation shown between blink occurrence and saccadic eye movements. The approach can be broken down into three major components.

First, spontaneous eye blink rate was measured in both real world and HMD viewing conditions. These measurements were compared to identify any effects of head mounted displays on blink rate. There was little reason to believe that HMDs would affect blink rate in primary gaze. It was therefore hypothesized that this value would remain largely unchanged.

Second, the probability of eye blinks accompanying saccadic eye movements were compared between HMD and direct viewing conditions. Different degrees of saccadic eye movements were examined to determine any relation between saccade magnitude and the probability of an associated blink during HMD use. It was suspected that there would be no difference between equivalent saccades performed with and without an HMD, as the corollary discharge which links saccades to blinks would be equivalent across scenarios. However, saccade magnitude may be limited by the field of view of the HMD. Saccades of smaller magnitude have been shown to be less likely to be accompanied by a blink (Fogarty & Stern, 1989). Therefore, saccade-coupled blinks may occur less frequently if saccade magnitude is limited. This case was accounted for in the third component of the study.

Third, gaze changes involving head rotating motions were analyzed to determine the probability with which accompanying saccades and blinks occurred. These motions are meant to emulate those which occur during normal HMD use. It was hypothesized that when using an HMD, the saccades which normally accompany head rotations would occur with less frequency and less magnitude due to the fixed optics of HMDs, lens distortions, limited field of view, and projections which do not match the user’s vergence angle. This, in turn, would cause a drop in associated blinks, as blink compulsion from any corollary discharge co-originating with orbital muscle motor signals would be weakened or eliminated.

By examining the tie between eye blinks and gaze changes at three levels of granularity, it was possible to not only identify any differences, but to make inference about the causes of these changes. While exploration of the numerous cofactors of blink rate are beyond the scope of this study, these are discussed in the literature review to establish a basis for future investigations.

Significance

With the emergence of consumer grade head mounted displays, these devices have seen more widespread use and more varied degrees of use. It is important to understand how such variations can affect ocular health of users. Similar studies were necessary following the adoption of the computer for home and business use. Those studies resulted in a set of best practices that have benefited the ocular health of computer users.

Consumer grade HMDs have also revitalized industry interest in virtual reality. Many engineering and architecture firms are already yielding fruit. However, the specialists operating industry VR systems are often exposed to the systems for extended periods. This is also true of content creators using VR in the entertainment industry. Not only do content creators have to put on an HMD to check their work, but tools allowing seamless production within headsets has taken hold. Unity Technologies has publicly released Editor VR, allowing creators to build, test, and edit content without ever taking off the HMD (Ebrahimi, 2016; Feltham, 2017). With increasing exposure times it is important to understand potential workplace stresses due to VR devices.

Content designers are in the midst of exploring the capabilities of HMD technology and establishing best practices. While much research has been dedicated to minimizing simulator sickness within HMDs, there is a relative void of work being done to maximize ocular health contributors. This study aims to establish an area of research within this field centered on blink rate. Research in this area could very well extend beyond hardware configurations to a set of content creation best practices. These best practices could apply to entertainment and industry applications of VR technology alike.

Research question

The overarching question of this study is whether blink rate is affected during head mounted display use. To achieve higher granularity and analyze the root cause of the observed blink rate, this question has been broken into three questions with quantifiable answers.

1. Is there a difference between blink rate when viewing the real world and blink rate during HMD use? This has been answered by comparing blinks per minute measured in a real world viewing condition to that measured in a HMD viewing condition. The null hypothesis was that no significant difference would occur.
2. Is there a change in the likelihood of blinks occurring with gaze changes during HMD use? This has been answered by calculating the percentage of gaze changes that are accompanied with a blink in both conditions, then comparing the two values. The null hypothesis was that blinks would occur with the same frequency in both conditions.
3. Do head mounted displays affect saccade amplitude during gaze shifts? Saccadic eye movements were counted and measured for each gaze shift, then compared across conditions. The null hypothesis is that frequency and amplitude of saccades during gaze shifts would be unaffected during HMD use.

Assumptions

There are multiple factors which are beyond total control and could affect the results of this study. Therefore, the following assumptions must be made.

It must be assumed that interest in HMD technology did not affect blink rate. For some participants HMD use was a new experience. This could have led to higher interest and increased attention. Increased attention to a task has been shown to reduce blink rate (Cardona & Quevedo, 2014; Drew, 1951; Fogarty & Stern, 1989).

Biological factors play a major role in determining blink rates. While much variability exists between individuals, the factors examined affect blink rate similarly in all, except those with certain medical conditions. Within subject methods were used to control for differences in blink rates between participants. However, this study assumed that fluctuations in biological factors were insignificant over the course of the experiment.

It must be assumed that changes in emotional factors contributing to blink rate were insignificantly over the course of the experiment. Blink rate has been shown to correspond to level of cognitive stimulation, conversation, dopamine levels, and even simulator sickness (Dennison, Wisti, & D'Zmura, 2016; Karson, 1983). Boredom and fatigue were identified as the most likely changes to emotional state. Experiment sessions were kept short to minimize these potential effects. Counterbalancing was also used to reduce order effects due to changes in emotional state. It was therefore also assumed that effects of boredom or fatigue specifically were minimal and insignificant.

Blink rate can suddenly increase in the presence of ocular irritants, as the eye tries to flush out the source of irritation. Experiment sessions were performed in a clean environment with a filtered HVAC system. It is therefore assumed that particulate or other ocular irritants did not affect the experiment results.

Glare has been shown to promote reflexive blinking. In bright or high contrast scenes, the Fresnel lenses of the HTC Vive can produce glare along their ring-shaped ridges. By using darker colors with low contrast in the HMD viewing condition glare can be minimize. However, it is an assumption that any glare still produced was not intense enough to produce reflexive blinks.

Limitations

Due to the scope and delimitations of this study, it had a number of limitations. These limitations may present weaknesses or affect the inferences which may be drawn.

This study did not examine symptom occurrence. Therefore, any conclusions drawn from this study have been limited to the single risk factor of blink rate, not the manifestation of dry eye. Because this study focuses only on blink rate, one cannot infer whether dry eye will occur.

In order to fit a camera inside of the HMD without inhibiting normal use, the camera must be mounted on the side. This arrangement limited observation to a side-view of the eye. This view prevented the precision of measurements of saccadic eye movements. That is, without a head-on view of the eye, magnitude and speed of an observed saccade was not able to be measured.

This study was primarily focused on showing any difference in blink rate due to the optics of HMDs. In order to eliminate variables which would affect blink rate and sample evenly across conditions, the given task was performed in a near-featureless environment. As such, the testing application used was atypical of programs run in HMDs. Changes in blink rate have been observed across different types of video games viewed on desktop monitors (Cardona, García, Serés, Vilaseca, & Gispets, 2011). This is due to the strong effects attention and visuomotor task complexity have on blink rate. Therefore, any effects shown in this experiment may not apply ubiquitously.

Delimitations

In order to perform this study, conscious delimitations of scope had to be made due to limited resources. While some choices added assumptions and limitations to the study itself, none were made that would compromise the study.

Effects of environment or stimulus textures, luminance, contrast, or colors on blink patterns have been excluded from this study. While visual suppression has been shown to depend on such factors, little research suggests that the relation between visual suppression and saccade concurrent blinks is one of causation rather than mere correlation. Such factors were too numerous to test individually. Testing so many variables would not have been possible in the timeframe of the project and would have hurt the statistical power of the results.

Demographics of participants were beyond the scope of this study. While some groups may be more predisposed to CVS symptoms, this study focused solely on the blink rate risk factor rather than symptom occurrence. It also was not in the interest of the study whether certain people groups are affected differently, as the purpose of this study was to identify risks associated with head mounted display technology itself. Within subject analysis lessened any need for such data to be gathered.

Testing across multiple head mounted displays was beyond the scope of this study. The purpose of the study was to indicate whether blink rate is affected by HMD use, not to compare the effect of different products.

Symptom occurrence was beyond the scope of this study. This delimitation was due to time and ethical constraints. Exposure times long enough to reliably induce symptoms would have made experiment sessions too long. Intentionally inducing a repetitive strain disorder in participants would not only have been unethical, but would have made it difficult to find willing participants.

Just as dry eye symptoms were out of scope, so were other dry eye risk factors. The second most cited risk factor is exposed ocular surface area, which changes with elevations of gaze. Because HMDs are designed for use with forward or primary gaze, it made sense to treat this variable as a constant.

Effects of ambient room temperature or humidity on spontaneous blink rate were also ignored. Both factors can affect both bodily and ocular comfort, which then can affect blink rate. Studying these factors would have made the scope too broad. Therefore, testing took place in a climate controlled environment where extremes and fluctuations of these factors were negligible.

Effects of vergence and smooth pursuit movements on blink patterns were also beyond the scope of this study. Vergence movements are often accompanied by saccades and are rarely isolated. Therefore, they would have a minimal effect on overall blink rate. Smooth pursuit motions have been shown to not be accompanied by blinks. Therefore, a reduction in accompanying blinks would not be causal. Additionally, smooth pursuit should not be affected by the field of view constraints which saccades face, as it can be accompanied by smooth head motion to keep the eyes within the field of view of the display.

Definitions

Computer vision syndrome – "Ocular symptoms related to computer use…" including "eyestrain, tired eyes, irritation, redness, blurred vision, and double vision. The major contributor to symptoms by far appears to be dry eye" (Blehm, Vishnu, Khattak, Mitra, & Yee, 2005, p. 253).

Direct Viewing – The viewing of a real object or scene via line of sight through a clear medium (Milgram & Kishino, 1994).

Fatigue – "the sensation experienced by the subject as a result of a strain exceeding some limit" (Jaschinski, 2002, p. 159)

Head-Mounted Display – A fully immersive display worn on the head in which lenses focus the image of a screen onto the wearer's retinas.

Palpebral aperture – The opening between the upper and lower eye lids.

Saccadic eye movement – Land (1999) defines saccades as fast movements "that shift the direction of gaze (p.341)."

Strain – "the physiological reaction induced by the stress" (Jaschinski, 2002, p. 159).

Stress – “the aspect of the task that induces bodily or mental tension” (Jaschinski, 2002, p. 159).

Virtual Reality – A completely synthetic environment in which the participant is fully immersed (Milgram & Kishino, 1994).

Visual suppression –

The phenomenon of visual suppression may appropriately be regarded as one means by which the visual system selects information. Stimuli which are perceived under many normal conditions are not perceived under certain conditions related to the temporal sequence of stimulation, the retinal areas stimulated, the form and luminance characteristics of the stimuli, and the oculomotor behavior of the perceiver (Volkmann, 1986, p.1401).

CHAPTER 2. REVIEW OF LITERATURE

Introduction

Computer vision syndrome is the main subject of this study. Decrease in spontaneous eye blink rate has been one of the most recognized contributors to computer vision syndrome. The goal of this review is to build an argument for investigating the effects of head mounted display use on blink rate and ocular motion accompanying gaze shifts. The first half is a review of literature computer vision syndrome. Symptoms, risk factors, and impacts are examined. The potential effects of head mounted displays are also discussed. The second half goes into detail about the eye blink's role in CVS dry eye and the link between blinking, cognition, and saccades.

Computer Vision Syndrome

The following sections review the literature on CVS symptoms, risk factors, and the impact of CVS. The connections between risk factors and symptoms are explained. Any effects that HMDs could have on risk factors are also highlighted. All major symptoms and risk factors are reviewed for the sake of completeness, even though many fall outside the scope of this study's experimentation. One of the goals of this study is to provide the foundation for future computer vision syndrome studies in head mounted displays.

Symptoms

Computer vision syndrome (CVS) is defined as a repetitive strain disorder in those who spend extended periods viewing computer displays. Blehm, Vishnu, Khattak, Mitra, and Yee (2005) categorize symptoms into four categories: Asthenopic, visual, ocular surface-related, and extraocular. Asthenopic symptoms include eye strain, fatigued eyes, and sore eyes. Visual symptoms include blurred vision, slowed accommodation, presbyopia or myopia, and double vision. Dizziness, disorientation, and headaches have also been reported. Such symptoms could be classified as either asthenopic or visual. Ocular surface-related symptoms include increased irritation from contact lenses and itchy, dry, or watery eyes. Extraocular symptoms are those bodily strains related to the ergonomics of computer display use. These include neck, back, shoulder, and wrist pain. Asthenopic, visual, and ocular surface-related symptoms have not been shown to have permanent effects. Extraocular symptoms, however, can develop into chronic conditions such as carpal tunnel syndrome.

Blurred Vision

Blurred vision occurs when the eye cannot properly focus light on the retina. This can occur due to exhaustion of the ciliary muscles, which control the accommodation of each eye; disability glare; monitor properties; or incorrect refraction in corrective lenses or the eyes. Blurred vision can occur both during or following extended display use. Persistent blurred vision is commonly blamed on the strain of maintaining near focus for extended periods. Such strain exhausts the ciliary muscles, limiting the possible range of accommodation until the muscles recover (Luckiesh & Moss, 1935; Ostberg, 1980). Chu, Rosenfield, Portello, Benzoni, and Collier (2011) observed blurred vision during short term display viewing, indicating conditions could cause blurred vision without straining the accommodative system. Display contrast and pixel density have been shown to affect picture clarity, resulting in the perception of blurred vision during display use (Blehm et al., 2005; Miyao, Hacisalihzade, Allen, & Stark, 1989; Thomson, 1998). Thomson (1998) also notes that because the viewing distance of monitors is typically greater than that of hard copies, they usually fall out of focus for those who wear reading glasses to correct hyperopia. Display brightness has been shown to affect clarity of vision. Brighter screens cause the pupil to constrict. With a smaller aperture, less accommodative work is required of the eye, resulting in clearer vision.

Blurred vision can also occur due to dry eye. The tear layer is the first and greatest change in index of refraction as light passes from the air into the eye. (Miljanović, Dana, Sullivan, & Schaumberg, 2007; Tavares, Fernandes, Bernardes, Bonfioli, & Soares, 2010). An eye with a compromised tear layer lacks its proper refractive properties, affecting its ability to focus. Hayes et al. (2007) showed a significant inter-correlation of 0.78 between blurred vision and dry eye symptoms. Blurred vision accompanying dry eye persists after display use is complete. It can become chronic if dry eye becomes chronic. Hayes et al. (2007) found that 10% of participants experienced moderate to severe blurred vision while 31% experienced slight or mild symptoms.

In HMDs, blurred vision during use may be caused by several factors: dirty lenses, pupils offset from lens focus, chromatic aberration, disability glare caused by Fresnel lens ridges, and low pixel density. Presenting text in consumer HMDs is a known issue, as they do not have the resolution to present fine text clearly. The discomfort of blurred vision as the pupil deviates from the focal point of the lens motivates this study's investigation into changes in saccade and blink patterns in HMDs. Some users of HMDs may also remove their glasses due to the difficulty of fitting the headset over them. Persistent blurred vision from extended HMD exposure has yet to be shown.

Double Vision

Double vision is the perception of two or more distinct images when only one would be normal. These images can either be overlapping or adjacent. Double vision can occur due to improper vergence or improper refractive properties of the eye. It can accompany dry eye, because the ocular surface no longer refracts light properly.

A similar phenomenon can also occur when a moving object is illuminated by a rapidly pulsing light source or if the light source itself is moving across the visual field. This effect is akin to that of a strobe light and can be seen in many places where pulse width modulation (PWM) circuits are used to control lights, including display backlights and LED taillights. Together, the pulsing light and persistence of vision create a trail of crisp overlapping ghost images across the visual field.

In HMDs, double vision may occur more frequently when viewing virtual objects closely. Because projection matrices do not update based of pupil positions, the images viewed through each eye become increasingly disparate with greater vergence. This results in the ability to fuse binocular images breaking down far sooner than in real world viewing conditions. Ghosting effects caused by PWM circuits have not been shown in HMDs. But, as the section on display flicker points out, the risk factors are present.

Dizziness, Disorientation, and Headache

Dizziness, disorientation, and headaches can arise from other symptoms, such as blurred vision, double vision, or asthenopic symptoms. They can also arise in isolation due to discomforts of display use such as discomfort glare or display flicker. These symptoms may also occur due to the stress or duration of a task rather that the display. Hayes et al. (2007) report that

31% of participants suffered slight to mild headaches, while 13% suffered moderate to severe headaches.

Dizziness and disorientation also show up in simulator sickness. It is therefore important not to interpret these symptoms as a clear sign of either CVS or simulator sickness. Other factors need to be considered to determine what is causing dizziness or disorientation in an HMD. Simulator sickness is likely to set in long before CVS symptoms, unless extended monitor use has preceded HMD use. Therefore, it is unlikely that symptoms from both sources compound.

Dry Eye

Common descriptions of dry eye include: itchy, irritated, red, bloodshot, scratchy, watery or dry eyes. Dry eye occurs when the protective tear layer is not replenished as quickly as it breaks down or evaporates (Patel, Henderson, Bradley, Galloway, & Hunter, 1991). The primary way the tear layer is replenished is though blinking. Tear breakdown time has been shown to shorten when the eye is open wider (Tsubota & Nakamori, 1995). The factors of blink rate and palpebral aperture are therefore considered the main factors in determining dry eye onset. HMDs are constructed for forward gaze and therefore assume the risk associated with wide palpebral aperture. The purpose of this study is to determine whether their use also affects the blink rate factor.

In ophthalmology, dry eye disease is considered separate from computer display exposure. It is “a multifactorial disease that results in symptoms of discomfort, visual disturbance, and tear film instability with the potential to damage the ocular surface” (Tavares, Fernandes, Bernardes, Bonfioli, & Soares, 2010, p.84). If any part of the lacrimal functional unit fails, tear stability can be compromised. The lacrimal functional unit consists of the lacrimal glands, the source of the aqueous component of the tear layer; the ocular surface; the eye lids, responsible for distributing tears across the ocular surface; the Meibomian glands, the source of meibum, the layer of lipids and proteins which slows tear evaporation; and the neural reflex loops which control these activities (Rolando & Zierhut, 2001). A number of factors have been shown to affect these systems including but not limited to: gender, age, diet, surgery, medications, and infections (Tavares et al., 2010).

Meibomian gland failure is the leading cause of dry eye disease diagnosis. The decrease in meibum in the tear layer results in a faster tear breakdown time. Patel, Henderson, Bradley, Galloway, and Hunter (1991) proposed that dry eye occurs when the tear breakdown time approaches or dips below the inter-blink period, because the tear layer evaporates faster than it is replenished. Therefore, if the tear breakdown time decreases due to a meibum deficiency, a reduction in blink rate would further exacerbate symptoms. This study is focused on failure of the eye lids to perform as desired; that is, the reduced blink rate associated with CVS. It is important to acknowledge that dry eye exists outside of CVS, but often is exacerbated by display use.

The prevalence of dry eye has been widely studied with varied results. Most studies agree that risk increases with age and that women are at higher risk. Farrand, Fridman, Zer Stillman, and Schaumberg (2017) estimate over 16 million adults in the US (6.8%) experience dry eye symptoms. The survey of 75,000 participants showed increased occurrence with age and among women. (Farrand et al., 2017) cite that dry eye is increasing in prevalence in younger adults. Schaumberg, Sullivan, Buring, and Dana (2003) estimate that dry eye affects 7.8% of US women over 50, that is, 3.2 million women. The study also showed an increase in prevalence with age. Computer use was not a factor in either study.

Hayes et al. (2007) collected surveys on CVS symptoms from 1000 Ohio State University employees who used computers for their jobs. The survey founds 38% of participants experienced slight or mild dry eye symptoms and 17% experienced moderate to severe dry eye symptoms.

Uchino et al. (2008) studied the prevalence of dry eye symptoms in computer display users at four Japanese pharmaceutical companies. They reported one or more severe CVS symptoms in 26.9% of male subjects and 48.0% in female subjects. The study found a lower occurrence of symptoms with age. The authors explain that this could be due to bias introduced by the sampling method.

Extraocular Symptoms

Extraocular symptoms are those that do not affect the eyes or the visual system. These symptoms include soreness in the neck, back, shoulders, and wrists. Extraocular CVS symptoms have also been called cumulative trauma disorders (CTDs) or musculoskeletal disorders (MSDs). Gerr, Marcus, and Monteilh (2004) argue that posture and time-on-task are the main risk factors for extraocular symptoms. In their review of epidemiology literature, they found that the keyboard height and arm support have consistently been shown to affect symptoms in the upper back, neck, and shoulders. Mouse position is a consistent factor in wrist symptoms. Hours spent typing was found to be most consistently linked to neck and shoulder pain.

Cho, Hwang, and Cherng (2012) analyzed survey data on neck, shoulder, and back pain in participants who spent more than seven hours a day using a computer. Frequency or symptoms ranged from 60% to 77.3%. In their meta-analysis, Cho, Hwang, and Cherng (2012) found other studies had reported extraocular symptoms affecting between 15% and 70% of computer users.

HMDs reduce some extraocular risks while increasing others. While they do promote standing and moving around more than a desktop display, they can also be used in a stationary position. Control schemes which require gesturing or reaching can cause repetitive strains. The added weight of devices, distribution of weight, and lack of support while standing must be considered when planning extended use.

Risk Factors

Many factors are thought to contribute to the wide array CVS symptoms. "Visual fatigue at a computer screen may result from several aspects of the task, e.g., eye movements, visual detection and discrimination, mental workload, or a short viewing distance that may stress convergence and/or accommodation" (Jaschinski, 2002, p. 164). In addition to the factors of visual fatigue, there are those of ocular surface and extraocular fatigue. The ones discussed in this review include: posture, palpebral aperture, glare, sustained near focus, display flicker, spontaneous eye blink rate, and biological factors.

Display Flicker

Early CVS studies examined the refresh rates of CRT monitors. Due to the mechanisms of the scanning cathode ray, these displays had a flicker rate that was just beyond the critical fusion frequency of human vision. The flicker of CRT displays has been credited as a major cause of asthenopic and visual CVS symptoms as well as general annoyance and discomfort (Thomson, 1998). Thomson and Saunders (1997) showed that by reversing the direction of the scanline, users could detect the motion. Through continued exposure, the perception of the flicker was reduced. Thomson and Saunders concluded that CRT flicker is always perceivable, but that the vision system learns to ignore it.

Berman, Greenhouse, Bailey, Clear, and Raasch (1991) argued that although flickers with frequencies above the critical fusion frequency are not perceived, the human retina is capable of sensing and generating signals at these frequencies. They recorded electroretinogram (ERG) signals corresponding to the frequency of flickering stimuli up to 200Hz, well beyond the perceptual critical fusion frequency. It is proposed that this may be the cause of discomfort from flickering light sources such as CRTs and fluorescent lighting. While LED backlit LCD monitors lack many of the flicker-related issues of CRTs (Blehm et al., 2005), the backlights do flicker at an unperceivable rate, using pulse-width modulation (PWM) circuits to control display brightness (US7348957B2, 2008). The rate of flicker varies. LCD backlights operating at lower PWM frequencies, together with persistence of vision, can cause visual anomalies when in motion or when illuminating an object in motion. This can be observed by waving a hand in front of such a display, or by rapidly moving a smart phone across the field of vision. In such a way, this effect can be observed in the display of an HTC Vive.

Berman et al. (1991) also, state that the ERG signals are stronger with increases in both luminance and the field of view a flickering stimulus occupies. Therefore, any detrimental effects caused by low frequency PWM flickering of backlights could be magnified in HMDs, in which much of the user's field of view is occupied by the display.

Glare

The word glare has been used in different ways in CVS literature. Sheedy, Smith, and Hayes (2005) described glare as two phenomena originating from the same source. Disability glare is a reduction in the ability to perceive an object when the surroundings contain a much greater luminance. The example giving is a driver's inability to see when the headlights of oncoming traffic shine in the driver's eyes at night. This is due to the scattering of the intense light across the viewer's retina, obscuring lower luminance stimuli. Discomfort glare is the discomfort caused by great disparities in luminance within the visual field (Hultgren & Knave, 1974). Wolska and Śwituła (1999) recommend a luminance disparity of less than 60:1 to avoid discomfort glare.

Other literature uses the term glare to describe reflections of the surroundings on the surface of displays. When such reflections are bright enough, they reduce contrast of the retinal image of that area of the display, reducing visibility. Such reduced visibility promotes asthenopic symptoms (Bergqvist & Knave, 1994; Blehm et al., 2005; Uchino et al., 2008). Reflective glare is another factor which differentiates reading hard copies from reading on a computer display, as paper copies are often diffuse and do not create hard specular reflections (Thomson, 1998).

Previous studies recommend strategies for reducing glare. Reducing the disparity of luminance between displays and the surroundings reduces disability glare and discomfort glare and makes reflections on displays less obstructive. Windows and other bright light sources should be kept out of the field of view of display users. Displays should be positioned so that bright light sources are not reflected on their surface (Sheedy et al., 2005). Anti-glare filters may be used to reduce reflective glare (Blehm et al., 2005; Uchino et al., 2008).

In the context of HMDs, glare from the environment does not pose much risk, as the headsets are enclosed. However, glare can emerge within the headset from the virtual environment. With advances in high contrast displays, high luminance disparities are possible. More research would need to be done to determine whether users experience disability glare or discomfort glare. However, reflective glare can be seen readily in HMDs built with Fresnel lenses. In high contrast environments specular reflections can be observed along the ridges of the lenses.

Sustained Near Focus

The accommodative strains from extended near field activity have long been thought to be a source of asthenopic CVS symptoms. Ostberg (1980) used laser optometry to show shifts in accommodation strength after prolonged visual display unit (VDU) use. Accommodation response was measured before and after a two-hour VDU task. Comparison to the two measurements revealed a hyperopic shift during near fixation and a myopic shift during far fixation after the VDU task. This narrows the range of depths at which the eye can focus. These shifts are thought to be a sign of strain in the ciliary muscles. The near and far accommodation responses both shift toward dark focus, the accommodation of the eye when in darkness, which thought to be a resting state. The observed shifts in accommodation response correspond with reports of blurred vision due to extended display use. Piccoli, Braga, Zambelli, and Bergamaschi

(1996) found similar accommodative shifts when studying the effects of VDU use in an office setting.

Chu, Rosenfield, Portello, Benzoni, and Collier (2011) compared symptoms of CVS between two near-accommodation tasks, reading from a backlit LCD monitor and reading from a printed sheet of paper. The testing environment was designed to minimize other stresses, isolating near-focus. The monitor was placed in an appropriately lit room to remove negative effects of contrast and glare. The paper copy was hung from the monitor to eliminate variations in posture and palpebral aperture. Luminance was measured and matched between the monitor and hard copy conditions. The results contained significantly higher reports of blurred vision when reading from the monitor, and higher median scores for other CVS symptoms under the monitor viewing condition. Chu et al. reject that near-focus associated with display use is the sole cause of blurred vision. It is of note that these findings do not mean that extended near-focus does not visual stress. Instead, it means that more factors are at play in addition to extended near focus. High monitor contrast could result in disability glare. Lower pixel density could affect picture clarity. The authors admit participant bias could have affected results and that the 20-minute test sessions could have been too short to elicit strong symptoms. Further, Chu et al. measured symptoms which occurred during the study. This differs from the persistent accommodative shifts measured by Ostberg (1980) and Piccoli, Braga, Zambelli, and Bergamaschi (1996) after longer sessions.

Effort required to maintain vergence during near fixation has also been tied to asthenopic and visual symptoms of CVS (Jaschinski, 1998, 2002; Owens & Wolf-Kelly, 1987; Tyrrell & Leibowitz, 1990). By measuring fixation disparity against view distance Jaschinski (2002) determines that individuals with greater propensity for visual fatigue have less accurate vergence systems during near viewing. He argues that vergence errors are responsible for visual fatigue at near viewing distances. Applied to HMDs, this means that systems with static projection matrices, which do not change based on pupil position, should excel at inducing visual fatigue during near fixation, because disparity is artificially introduced. With advances in eye tracking, this problem could be resolved. If fixation disparity is as constant as Jaschinski (2002) claims, with such advances, tracking systems could also be calibrated to compensate for the user’s natural fixation disparity, leading to better-than-life, stress-free near fixation within HMDs.

Posture

Posture is largely responsible for extraocular computer-related strains. Myopic computer users often report neck pain due to a tendency to lean toward the display. Hyperopic computer users may tilt their heads back into an uncomfortable position to view displays through corrective bifocals (Occupational Safety and Health Administration, n.d.; Thomson, 1998). This can lead to muscular fatigue in the neck. Similarly, tilting the head back to view displays above eye level can result in neck strain. Neck and back pain can also arise due to extended periods of sitting without proper support, as explained on the OSHA computer workstation website. Improper chair or desk elevation has been shown to increase risk of shoulder and wrist pain when using keyboard or mouse inputs.

For extraocular symptoms HMDs seem to solve much of what makes desktop monitors so problematic. HMDs promote standing and moving around. Input devices are commonly handheld, freeing the user's posture. However, extended periods of standing and repeated gestures and poses can also lead to repetitive strains and exhaustion. The neck must support the added weight of the HMD. The body must also support itself instead of distributing weight across a chair. These are factors which should be considered when evaluating the extraocular risk factors of extended HMD use.

Posture can also affect asthenopic and visual symptoms by affecting palpebral aperture, the size of the opening between eyelids. Downward gaze is accompanied by the smallest opening, followed by forward gaze, then upward gaze with the largest opening. This observation has given rise to hypotheses explaining the differences in symptoms experienced while reading from hard copies versus text on displays. Assuming text is placed below eye level while reading, whereas displays are typically placed closer to eye level; many consider that the narrow palpebral aperture associated with downward gaze may be responsible for the lower rate of reported symptoms while reading hard copies (Blehm et al., 2005; Rosenfield, 2011; Sotoyama, Villanueva, Jonai, & Saito, 1995).

Palpebral Aperture

As describe above, palpebral aperture is the degree to which the eyelids are open. It has been proposed that strains on the ciliary muscle are minimized as the palpebral aperture narrows to a point where the eye lids partially obstruct the pupil. The smaller exposed opening naturally allows a wider range of focal distances without accommodation, similar to how a pinhole camera works without a lens. This is why squinting helps the eyes focus. During downward gaze the upper eyelid partially covers the pupil as the palpebral aperture shrinks (Thomson, 1998). This is one factor in explaining why reading from hardcopies leads to less asthenopic and visual symptoms than reading from computer displays.

In addition to relieving accommodative strains, a narrow palpebral aperture has been shown to lessen factors that contribute to dry eye. Tsubota and Nakamori (1995) conducted a study relating exposed ocular surface area to tear stability. To do this they observed tear evaporation rates of participants during downward, forward, and upward gaze. They found that an increase in exposed ocular surface area not only increased the evaporation rate of the tear layer overall, but also the evaporation rate per unit of exposed area. This provides an explanation for the lower risk of ocular desiccation while reading hard copies versus reading from a display.

Spontaneous Eye Blink Rate

Blink rate is well documented as one of the primary contributors to dry eye symptoms. Portello, Rosenfield, and Chu (2013) showed significant correlations between blink rate, percentage of incomplete blinks, and dry eye symptoms. Additionally, it has become ubiquitously accepted, through repeated observation, that blinks rates slow during display usage (Cardona et al., 2011; Patel et al., 1991; Schlote, Kadner, & Freudenthaler, 2004).

In the study by Patel, Henderson, Bradley, Galloway, and Hunter (1991), a significant decrease in blink rate was shown during display use compared to that during conversation with the investigators. These findings align with other which have found slowed blink rates during monitor use and reading as well as increased blink rates during conversation. The novel portion of the study established the relationship between blink rate and the stability of the tear layer. Tear thinning time was shown to be unaffected by display use. However, blink rate slowed to the point where the inter-blink period came within range of tear thinning time. Because of the role eye blinks play in replenishing the tear layer, these findings provide physiological evidence that blink rate is an important factor in dry eye risk.

Completeness of blinks has also received attention as a possible dry eye risk factor. While Portello et al. (2013) argue that incomplete blinks fail to restore the tear layer, leading to increased dry eye risk; Harrison et al. (2008) showed that, in patients with chronic dry eye disease, tear layers break down more quickly after complete blinks. The conclusion is that complete blinks spread tears too thin in those with tear deficiencies. Tavares et al. (2010) argue that dry eye disease is primarily a pre-existing biological condition exacerbated by poor blinking. For such individuals, complete blinks may not reduce dry eye risk.

Impact

Quality of Life

Computer vision syndrome has been shown to correlate with a decrease in perceived quality of life. Hayes et al. (2007) showed the significance of asthenopic, visual, and ocular surface-related symptoms when evaluating self-reported metrics of quality of life, a multidimensional composite of life stress and life satisfaction (Aaronson, 1988). Aaronson's model of quality of life includes physical, functional, psychological, and social factors. Hayes et al. (2007) showed eye symptoms to be significantly correlated with life stress. The sample included 638 participants, who averaged 6 hours of daily computer use.

Productivity and Quality of Work

Miljanović, Dana, Sullivan, and Schaumberg's (2007) survey results show those with dry eye symptoms are more likely to have difficulty reading, preforming at work, using computers, watching television, and driving. Slowed reading rates have been shown when reading from a computer screen compared to reading from paper (Bergfeld Mills & Weldon, 1987; Mangen, Walgermo, & Brønnick, 2013; Muter & Maurutto, 1991). This is not always the case as shown by Muter and Maurutto (1991). The effects depend on many factors. It often accompanies visual stress sources such as small font, low resolution, low contrast, or glare (Bergfeld Mills & Weldon, 1987). Therefore, CVS can be an indicator that reading performance is hindered, as it is the result of prolonged exposure to these stresses.

In addition to physiological constraints, the human factor plays a central role in productivity and quality. For example, productivity may drop due to dissatisfaction with a low perceived quality of life or job quality (Menezes, 2013). When an employee recognizes their job is fatiguing, job satisfaction may drop (Hayes et al., 2007). Quality management research has shown that employee job satisfaction has a positive correlation to customer satisfaction, which is a defining characteristic of quality (Akdere, 2009; Brown & Lam, 2008). Therefore, stresses that negatively impact job satisfaction should be minimized to help ensure quality. Low job satisfaction also leads to poor employee retention (Eskildsen & Nussler, 2000; Schlesinger, Heskett, Trypuc, & Heller, 1991). Any resulting loss of human capital increases the cost of operations and can reduce customer loyalty or delay production (Hsu & Wang, n.d.).

Spontaneous Eye Blink Rate

Definition and Function

Karson (1983) defines spontaneous eye blinks as “bilateral paroxysmal brief repetitive eye closures that occur continuously and in the absence of obvious external stimuli (p. 643).” Therefore, spontaneous eye blink rate (SEBR) can be defined as the rate of unintentional eye blinking that occurs regularly without outside stimulation.

Many factors have been examined in attempts to understand what determines blink rate. In ergonomics and computer vision syndrome studies posture, palpebral aperture, level of comfort, air flow, particulates, and glare are all considered. In psychology and vision research dopamine response, stimulation, vocalization, and attention have all been shown to be driving factors behind SEBR.

The role of spontaneous eye blinks is to keep the eye clear of debris and restore the protective tear layer. Eye blinks drive tear flow when orbicularis oculi muscle contractions create pressure gradients along lacrimal ducts (Becker, 1992). As discussed by Rolando and Zierhut (2001), blinking increases the thickness of the tear film’s lipid layer by spreading the secretions of the Meibomian glands. Blinking, therefore, plays an essential role in tear dynamics, as it both rebuilds the tear film and promotes drainage (Schlote et al., 2004). The tear film also protects the ocular surface from being damaged by friction against the eye lid during closure and blinking (Rolando & Zierhut, 2001).

Measurement Methods

In the literature, SEBR is reported in blinks per minute. This rate is averaged over periods of two to five minutes, as the exact intervals and patterns vary greatly (Doughty, 2001; Schlote et al., 2004). Because SEBR only counts the number of blinks which occur over long periods, information about the timing and quality of blinks is lost. A more granular method of measuring blink rate is the inter-blink period or inter-blink interval. Inter-blink period is measured for each blink and has been used to analyze distributions, examine factors which trigger short-term changes in blink patterns, and measuring blink rates against tear breakdown times (Patel et al., 1991; Ponder & Kennedy, 1927).

Portello et al. (2013) measured the completeness of blinks against reports of CVS symptoms. Blinks where the upper eye lid does not meet the lower are considered incomplete. They argue that incomplete blinks are an equally significant factor of dry eye as reduced blink rate. However, Harrison et al. (2008) showed that complete blinks may do more harm than good in certain individuals. How do we handle partial blinks in the analysis of blink rate? Doughty (2014) used a compelling compromise by including incomplete blinks that covered at least half of the eye or occluded the pupil. While blinks of this nature do not fully combat ocular surface irritation, they facilitate critical optical function without spreading the tear layer so thin that it is compromised.

Categorization

Spontaneous eye blink rate has been categorized into three distinct groups types: reading SEBR, primary gaze SEBR, and conversational SEBR (Bentivoglio et al., 1997). Doughty (2001) found that these groups are indeed distinct through a meta-analysis of existing research. Doughty argued that in blink rate analysis, the task at the time of measurement should be considered within the context of these groupings to determine if a measured SEBR is "abnormal."

Primary gaze or resting SEBR is suggested to serve as a default or baseline value, as it is often measured in silence with no stimulation. Ponder and Kennedy (1927) showed no significant difference when this value is measured in the dark. They also observed normal SEBRs in the blind, concluding that neither vision nor the integrity of the vision system is required to promote normal blinking.

Reading blink rate is slowed due to attention to visual stimuli. Blink patterns while reading have be observed to correspond with line breaks, page breaks,(Doughty, 2014) and punctuation (Orchard & Stern, 1991). Coordinated blink patterns have even been shown during music sight reading (Fink, 2014).

Conversational SEBR is speculated to be heightened due to the mental activity and stimulation of vocalization (Doughty, 2001; Ponder & Kennedy, 1927). Ponder and Kennedy observed the elevated blink rates of witnesses testifying in court. While confirming that conversation does elevate SEBR, Doughty (2001) argues that too many variables affect conversational SEBR for standardized practices to exist between studies; that emotional responses to conversations and opinions of subjects greatly affect the stimulation from the conversation.

Causes

Reflex

Reflexive blinks are considered separate from spontaneous blinks, because they are in response to outside stimuli, and are not part of the regular blink pattern. Objects observed approaching the eye, contact with the eye or eye lashes, discomfort glare, and loud noises a few examples of stimuli which can provoke reflexive blinks.

Ponder and Kennedy (1927) found that cigarette smoke increased blink rate. They found that evaporation of the tear layer did not lead to increased blink rates. Blink rates with anesthetized corneas and conjunctiva were found to be no different than blink rates under normal conditions. Anesthetization did eliminate the effects of cigarette smoke on blink rate. Ponder and Kennedy concluded that reflexive blinks can be caused by irritants, but that the quality of the ocular surface is not the main cause of spontaneous eye blinks.

Reflexive blinks have been found to increase overall blink rate. Doughty (2014) reported an increase in spontaneous eye blink rate in the presence of a glare-producing light source. The glare phenomenon is due to the scatter of high intensity light, which in turn makes perception of adjacent objects difficult. This effect was increased further when gaze was directed closer to the glare source. Participants were seated facing a whiteboard two meters away. A sheet of paper with a large black cross printed on it was hung on the whiteboard as a visual target. Participants were split into two treatment groups and each was recorded three times. The first group was recorded once with the cross at eye level, once with it nine degrees below eye level, and once with it nine degrees above eye level. The second group was recorded once with the cross at eye level with no glare light, once with the cross at eye level with the glare lights, and once with the cross nine degrees above eye level with the glare lights. The glare lights were two tungsten lamps directed at the reflective surface of the whiteboard above eye level. While Doughty reported a higher SEBR, it would be more appropriate to consider these blinks to be reflexive rather than spontaneous as they are in response to an adverse visual stimulus.

In the context of HMD design, glare should be an important consideration. As light passes through both a strong focusing lens and the lens of a user's eye, glare compounds. This can readily be seen in modern HMDs which use Fresnel lenses. Kreylos (2016) documents this with photographs in the Glare Test section of his blog post on the optical properties of current HMDs. As high dynamic range display technology advances, the glare issue may become worse as higher contrast ratios become possible. Therefore, content and hardware creators must be aware of glare. The findings of the Doughty (2014) suggest that glare could be used as a cue to increase blink rate. However, this would create additional discomfort and inhibit clarity of vision, limiting its practical applications.

Discomfort

Physical or emotional discomfort have been shown to affect SEBR. Ponder and Kennedy (1927) claimed that elevated blink rates can be driven by unresolved "mental tension," such as anxiety, anger, or excitement. They claim it is similar to other motions such as fidgeting.

Dennison, Wisti, and D'Zmura (2016) argue that spontaneous blink rate, along with other physiological functions can be used as a measure of simulator sickness or "cybersickness." They measured blink rate during HMD use, filtering saccade associated blinks from their records. This data was analyzed against the subjects' responses to the Simulator Sickness Questionnaire. Dennison et al. concluded that the discomfort caused by the mismatch of sensory input in HMDs triggers multiple physiological responses, including increased blink rate. Therefore, simulator sickness should be considered as a factor in predicting SEBR. Interestingly, the average baseline SEBR within the HMD was less than that with monitor use. This may be due to task order effects, as the monitor condition always preceded the HMD condition. However, the blink rate at the end of the monitor condition was slightly higher than that at the beginning. This combined with the knowledge that a five-minute rest period followed each session leaves doubt of any task order effects. Novelty of the technology for participants unfamiliar with HMDs could have affected SEBR through means of heightened interest and attention. The two-minute baseline period also falls drastically short of the minimum five-minute measurement period recommended by the literature (Doughty, 2001). However, this finding supports the merit of the current investigation.

Dopamine

Karson (1983) examined the SEBR of subjects with abnormal dopaminergic activity under the speculation that central dopamine responses modulate SEBR. The groups sampled in this study included monkeys injected with dopamine agonists and antagonists; patients with Parkinson's disease, which is associated with decreased dopaminergic activity in the nigrostriatal pathway; and patients with schizophrenia, which is associated with increased dopaminergic activity in the mesocorticolimbic projection. A strong case was made for the involvement of dopamine pathways in SEBR. Parkinson's patients showed very low blink rates which could be altered through drug administration. Schizophrenic patients showed abnormally high SEBRs. The blink rates of monkeys were increased with doses of dopamine agonists. This increase was then eliminated by injections of dopamine antagonists. Additional drugs were administered to test for serotonin effects. None were observed. This study supports the idea that cognitive demands modulate SEBR, as dopaminergic pathways are known to play central roles in attention control, active memory, motor control, and problem solving.

Activity

The observation of task-dependent SEBR leads to the most compelling hypothesis for determining blink rate, that cognitive load and attention requirements of task modulate not only the frequency but also the timing of blinks. This explanation is widely accepted in CVS studies. Schlote, Kadner, and Freudenthaler (2004) concluded that decreased blink rate when using visual displays is due to increased levels of attention. This conclusion is supported by Cardona, García, Serés, Vilaseca, and Gispets (2011) who examined differences in blink rate when playing two video games of different pace. Both games showed significant differences in SEBR from primary gaze, as expected. The SEBR between games was also shown to be significant.

Evidence for attention modulated SEBR is far from limited to CVS research. Similar conclusions were reached in a study by Drew (1951) in which participants traced an oscillating line. The line was plotted on a long sheet of paper which scrolled from right to left so that participants could see the approaching waveform. Participants turned a steering wheel, which in turn moved a pencil, positioned on the left end of the apparatus, perpendicular to the direction of the scrolling motion. Blink rates slowed during oscillations and returned to resting rates when the line was straight. During erratic oscillations of the line, blinking halted. Just prior to such periods, participants were observed performing a blink, presumably in preparation for the focus that was about to be required of them. It was concluded that, during periods of intense fine visuomotor control, blink compulsion was suppressed.

Karson (1983) exposed an important differentiation to be made when discussing attention-modulation of SEBR. While attention to visual cues has been shown to reduce blink rate, careful attention to auditory information was accompanied by SEBRs significantly higher than those observed during conversation. This was done through the use of an oral memory exercise. Participants listened to the reading of a paragraph and then were tasked with reciting the paragraph from memory. During both the listening and the recitation, SEBR was higher than during normal conversation. This study was inspired by Ponder and Kennedy's (1927) observations of increased SEBR during testimony in courtrooms. Karson (1983) claims that this increase is due to the mechanisms of memory access, though this may not apply to visual information according to the finding of Shin et al. (2015). In the context of increasing SEBR during HMD use, the findings of Karson (1983) indicate that content creators who rely solely on visual cues when crafting VR experiences may increase the risk of CVS during use of their application.

While intense audio memory exercise increases blink rate, Shin et al. (2015) observed an inverse relation between blinking and visual information retention. The study consisted of a showing of a nature documentary. During the showing blink rates were monitored electronically. Participants reported their most memorable scene after the showing. Four weeks later, participants described and ranked scenes based on how much they could remember. Blink rates were overall lower than baseline during the showing, with the most remembered scenes from the documentary concurring with significant further reductions in blink rate. Information retention was also found to be higher with regard to scenes where lower blink rates were observed. The authors conclude that blink rate may be a good indicator of visual concentration.

Nakano, Yamamoto, Kitajo, Takahashi, and Kitazawa (2009) showed a synchronization of blink patterns across the audience of a movie theater. They argue that the attentional demands and mood of audience members were likely synchronized due to the shared viewing experience. Shared blink patterns were merely an outward expression of this synchronized cognitive state. These synchronized blink patterns indicate that people have similar blink responses to media crafted to guide attention and emotion. With this in mind, content creators can craft VR experiences that promote healthy blink habits. Additionally, any blink analytics during development should be considered indicator of future consumer response.

Gaze Shifts

One of the most strongly correlated factors of eye blinks is saccadic eye movement. Fogarty and Stern (1989) provide an excellent example of this correlation and also how it is affected by cognitive processes. The apparatus used consisted of five stimulus presentation locations and a chair for the participant. Stimuli were presented either centered directly ahead, 15º to the left or right, or 50º to the left or right. Stimuli were marked with an alphabetic letter. The participant sat in the chair with head pointed forward, using only eye movements to detect and identify peripheral stimuli. In one condition the task was to indicate when a peripheral stimulus was present. The other condition consisted of a set of stimuli presented in series, the first always being presented at the center location. The task was to indicate when the letter marked on the second stimulus matched that marked on the first.

Blinks were shown to occur with great likelihood in association with larger saccadic eye movements. Saccades moving the eye back to a centered gaze corresponded to more blinks than saccades toward a stimulus. This finding illustrates that attention is capable of modulating blinks that occur due to saccades. Fogarty and Stern concluded that the correlation between saccades and blinks is a mechanism for reducing information loss. Blinks are suppressed when shifting gaze toward a stimulus of interest. However, blinks and saccades often occur concurrently as both blinks and saccades cause interruptions in the stream of visual information. This loss of information is in part due to the occlusion of the pupil by the eyelid and in part due to visual suppression.

Saccade induced blinking could prove a useful tool for reducing CVS symptoms, and is unique to VR applications. Cardona and Quevedo (2014) concluded that time-locking between large saccades and blinking offsets the decrease in blink rate observed during tasks of increasing complexity. Blinks and saccades were video recorded during a sixty-minute driving route. Driving tasks varied by complexity of route and traffic. Large saccades were found to be more frequent during high-complexity tasks. Blink rate was surprisingly unaffected by task complexity. The authors attribute this to the greater frequency of large saccades, which were, across all conditions, accompanied by eye blinks with an average probability of 87.5%. This value is similar to that found by Fogarty and Stern (1989). While the aim of the study was to examine blink rate as a function of both task complexity and requirements for gaze shifting, these two inverse effects appear to cancel out. Saccade-coupled blinks also accounted for about half the total blink rate for all levels of task complexity.

Cardona and Quevedo (2014) offer an example of an activity that requires both concentration on a visuomotor task and frequent shifts in gaze. The results showed a blink rate that not only remained constant, but was at the upper end of normal blink rate along with that during conversation. If similar ocular behavior takes place during HMD use, dry eye symptoms may be less likely to occur. Therefore, it may be beneficial for content creators and industry VR specialists to design interactions that make use of similar, frequent, large amplitude saccades.

Fogarty and Stern (1989) proposed that the concurrence of saccades and blinks is a mechanism for reducing the total amount of time that vision is suppressed by overlapping sources of visual suppression. There is little evidence to suggest that visual suppression causes gaze-evoked blinks. There are many other sources of visual suppression, none of which produce a blink response. As Ponder and Kennedy (1927) point out, gaze-evoked blinks start occurring in infants even before spontaneous blinks. So it does not seem to be a learned trait either.

The mechanism that couples blinks to saccades is thought to be a corollary discharge. This is supported by the observation that blink onset occurs prior to saccade onset (Evinger et al., 1994). This would require motor commands to be sent to both the muscles responsible for saccades and blinking at the same time, rather than the blink impulse being a reflex to the gaze shift. That is, rather than saccade-coupled blinks being a response to disrupted vision caused by saccades, they are made in anticipation. Evinger et al. (1994) traced the neural pathways they believe carry this corollary discharge.

Summary

This literature review has attempted to expose a gap in the understanding of the effects of HMD use. The symptoms and causes of computer vision syndrome have been described. Dry eye has been cited as the most common CVS symptom (Cardona et al., 2011), and often acts as a cofactor of other symptoms. Spontaneous blink rate has a well-documented role in dry eye symptoms. Therefore, blink rate was chosen to be the focus of this study. Spontaneous eye blink rate, contributing factors, and the role of dopamine have been reviewed. Modulation through attention and gaze changes have been identified as two main factors in determining spontaneous blink rate. Attention has even been shown to suppress gaze-evoked blinks.

This review proposes that frequent gaze changes within head-mounted displays may help in the prevention of the dry eye symptoms of CVS by promoting blinking. Saccadic motion has already shown a strong correlation with blinking. Therefore, monitoring of ocular behavior in HMDs was central to this study. The hardware configurations of modern HMDs differ from natural vision in several ways. Narrower fields of view, lens distortions, and improper vergence projections may encourage gaze shift via head motion over saccadic eye movements, potentially removing the corollary discharge component of blink compulsion during gaze shift. The goal of this study was to identify any tendencies toward head motion instead of eye motion during gaze shifts, as well as to monitor blink rates and blink occurrence during gaze shifts.

CHAPTER 3. METHODOLOGY

Framework and Methodology

While there is a great deal of literature on the topic of computer vision syndrome, this field of study has yet to be expanded to include head mounted displays. With the use of desktop monitors, a reduction in spontaneous eye blink rate, which leads to symptoms of dry eye, has been heavily documented (Blehm et al., 2005; Rosenfield, 2011; Thomson, 1998). This reduction has been attributed to the visual attention that the tasks commonly associated with displays demand. However, head mounted displays and the freedom they provide are suited for a much different set of tasks. Therefore, the question remains, how do spontaneous blink patterns manifest during head mounted display use? This question is far too broad to be answered within the scope of this study. Many factors affect spontaneous blink patterns, each of which requires isolated attention (Doughty, 2001). This study focused on one factor that differentiates head mounted display use from desktop monitor use: large gaze changes. For example, when viewing a 23 inch monitor from a distance within OSHA's recommended range of 20 to 40 inches, the width of the monitor would span between 28.7 and 54.3 degrees of view. While Evinger et al. (1994) and Fogarty and Stern (1989) both found blinks coupled with saccades over 15 degrees in magnitude, Fogarty and Stern reported blink onset was most reliable when saccade magnitude was 50 degrees or higher. Such movements are far more likely to occur in HMD applications which promote the use of all six degrees of freedom.

In direct viewing of the physical world, spontaneous eye blinks have been shown to be time-locked with saccadic eye movements, with probability of blink onset increasing with saccade magnitude (Fogarty & Stern, 1989). By extension, head rotations made to shift gaze see a similar correlation due to the accompanying saccades. In head mounted displays, the approximated vergence projections, fixed accommodation, screen door effect, lens distortions, and limited field of view all make slight alterations to the viewer's perception. The goal of this study was to identify differences in saccade dynamics and blink patterns during gaze changes that could arise from these alterations.

An experiment was conducted, utilizing a setup similar to that of Fogarty and Stern (1989), to gauge the effects of HMDs on blink rate during measured gaze changes. The experiment was designed to search for effects on three dependent variables: blink rate, gaze-evoked blinks, and saccade magnitude. Understanding these relations would help make informed predictions about blink related dry eye symptoms.

Research type

This study was a controlled quantitative experiment. The control condition consisted of repeated intentional gaze changes made without an HMD. The experimental condition consisted of such gaze changes made while wearing an HMD. It was structured for within subject analysis using a crossover model. A model supporting within subject analysis was selected due to the numerous biological effects on blink rate and wild variation between people. The crossover design also supplied counterbalancing, minimizing order effects. Conditions were tested back-to-back to prevent outside events from affecting the participants' performance.

Population

The population covered by the sampling includes men between the ages of 20 and 30. The selection criteria also limit the represented population to those with fair eyesight. Those with interpupillary distances which fall outside the calibration range of the HTC Vive were also not represented in this study, as the discomfort resulting from poor calibration could have been a nuisance variable (Dennison et al., 2016).

Sampling approach

A review of literature on spontaneous blink rate shows a variety of sample sizes used. A common sampling is between 16 and 25 participants. A multiple of six subjects was required to maintain the balance of the selected crossover model. The target number of participants was therefore 18, though, due to a scarcity of applicants and the strict vision criteria, only 7 ended up participating.

Criteria

To qualify, participants were required to either pass a vision test or show proof that they met the vision requirements. It was required that any myopia need less than two diopters of spherical correction, any hyperopia less than one diopter of spherical correction, and any astigmatism less than one diopter of cylindrical correction. Prism correction was a disqualifier. All participants chose to present eye exam records. These requirements were included to ensure participants could see clearly in the Vive without corrective lenses. Corrective contacts can affect blink rate by causing ocular surface irritation. Glasses frames would have obstructed the cameras used for analysis.

To ensure participant safety, they were asked whether they had a history of seizures or upper back or neck trauma. All participants were also required to be 18 years or older to give informed consent and to ensure fully developed visual systems.

Recruitment

Fliers posted on public bulletins and distributed through email lists proved ineffective. All participants were personal contacts and colleagues. Despite this, the criterion that participants be naïve of the details of the study was upheld. The subject pool consisted of seven individuals, though one participant's data was discarded due to a misunderstanding of the instructions. All seven participants were male between the ages of 20 and 30. Four female candidates applied, but did not fulfill the vision requirements of the study.

Variables

The Vive tracking puck was used to record head orientation relative to the center line of the apparatus. Measurements were recorded in degrees from center, negative values meaning the subject was facing left, positive values meaning they were facing right. The angle was calculated by projecting the forward vector of the tracker to the floor plane, normalizing it, and calculating the angle between it and the forward vector of the apparatus. Measurements were taken approximately sixty times a second. Change in rotation over the course of a single gaze change was calculated by finding the difference between the minimum (left-most) and maximum (right-most) angles recorded during the trial.

The variables extracted from footage of participants' blink patterns were: blink time, measured in seconds since the beginning of the trial set; blink completion, categorized as full or partial depending on whether the eye lid covered the iris or not; blink coupling, categorized as coupled or independent based on whether the blink occurred concurrently with a saccade or not. These variables were found for each blink. Blink time was then used to calculate the inter-blink period for each pair on sequential blinks, in seconds.

Visual suppression has been shown to be affected by environmental variables such as luminance, contrast, special frequency, color, shape, and patterns (Volkmann, 1986). While the relation between gaze evoked blinks and visual suppression proposed by Fogarty and Stern (1989) does not seem to be causal, awareness of these variables allowed special care to be taken to keep them constant through faithful replication between virtual and physical environments.

Assessment instruments

The experimental apparatus consisted of four main parts. Each part has been classified as either an environmental apparatus or a measurement apparatus.

Environmental Apparatus

The purpose of the backdrop apparatus was to both serve as a mounting surface for the gaze targets and to create a visual field with high uniformity and low special frequency. The apparatus consisted of two parts: the physical construction and the digital reconstruction. The physical construction was used during the direct viewing condition. The digital reconstruction was used during the VR condition to mimic the environment of the physical construction.

Physical Construction

The physical construction consisted of blank white cloth stretched over a cylindrical PVC frame, 2.5m in diameter and 1.4 m in height. PVC pipes were cut to length and then bent over a jig using a heat gun. A chair for participants was positioned in the center of the cylinder. Two 2.5

cm by 50 cm strips of black cloth were pinned to the white fabric as gaze targets during testing, separated by arc angles of 15, 32, and 100 degrees.

The bending jig was created by fixing one end of a string to a table and tying a pencil to the string 1.25m from the fixed point. The string was pulled taut as the pencil was used to draw an arc with a radius of 1.25m on a sheet of plywood. Screws were then driven into the plywood about 2 inches apart, leaving over an inch of each screw protruding. The each pipe was pressed against the exterior of the arc created by the screws as it was heated and bent to fit the curve.

Eight five-foot sections of pipe were cut and bent to the correct arc, four for the top and four for the bottom. One side of the cylinder was left open to allow easy access into the apparatus. The bent pipes were joined by T fittings and elbow fittings were used on the open side. The vertical supports connected to the T fittings were bent away from the center on the cylinder to prevent them from pressing into the fabric and creating wrinkles and deformations on the smooth surface. The vertical supports on the open side of the cylinder were left straight to provide rigidity.

The white fabric was hemmed at the top and bottom with a loop to pass the frame through. Openings were left in the hem to line up with the pipe fittings and allow the vertical supports to pass through. Assembly involved first sliding all eight of the arced pipe into the hem, then attaching the fittings through the gaps in the hem, then attaching the vertical supports and smoothing out the fabric.

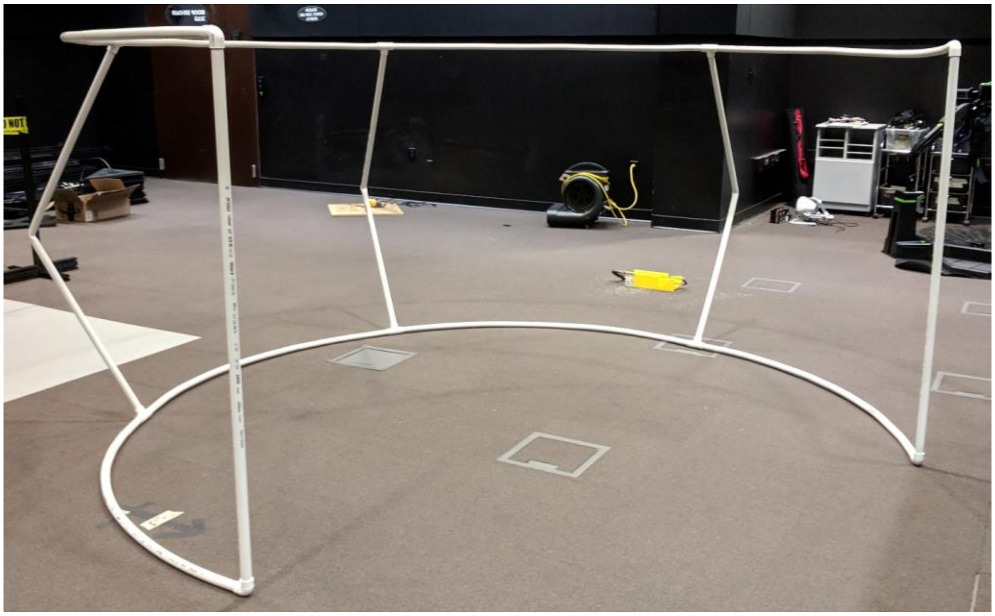

Figure 1. The PVC frame of the physical construction of the backdrop apparatus.

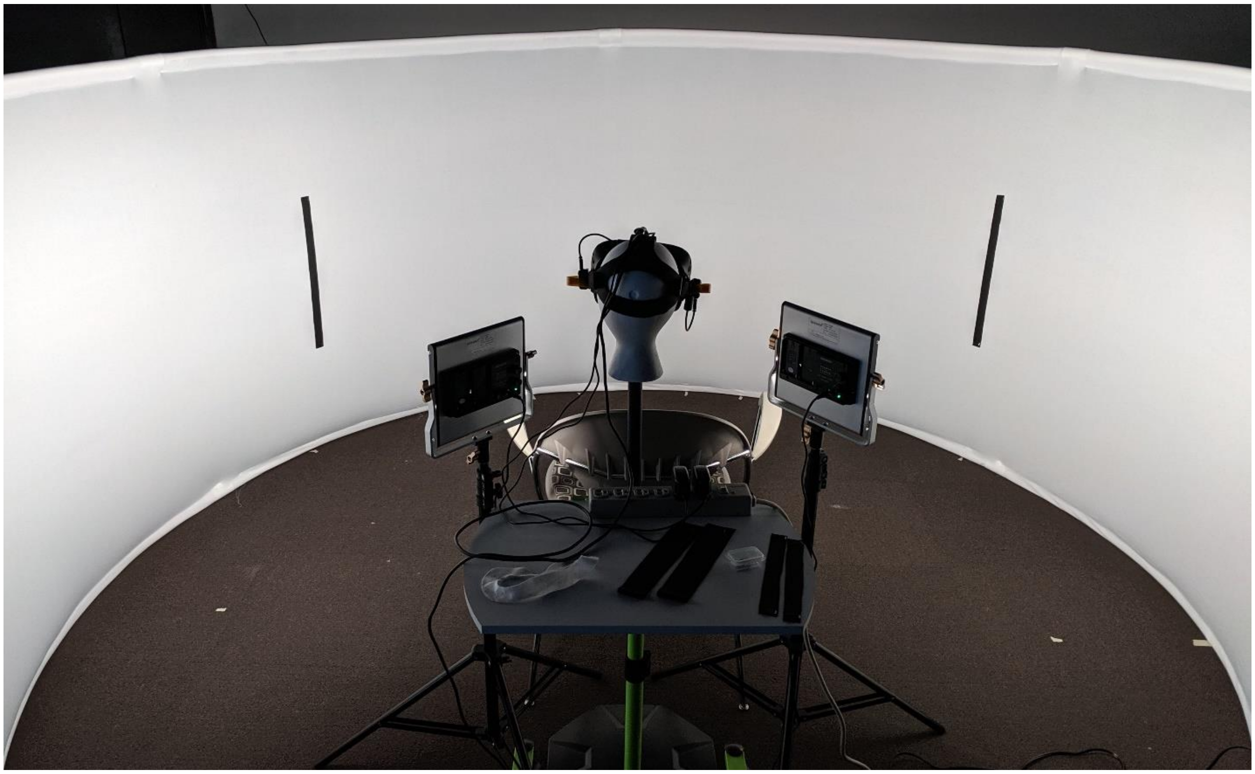

Figure 2. The backdrop apparatus as viewed during the direct viewing condition, 100 degree separation treatment.

Once assembled and in position, a protractor and string taped to the floor in the center of the cylinder were used to measure the 15, 32, and 100 degree arcs that would separate the gaze targets. Arcs were confirmed and centered using trigonometry and linear measurements aligned with the square floor tiles. Pins were inserted into the bottom hem of the white cloth to mark the ends of each arc. The hem concealed the pins from view for the participants, but allowed for quick placement of gaze targets during experiment sessions. A slight horizontal crease centered in the fabric helped place gaze targets vertically.

A chair for the participant was placed at the center of the cylinder with a diffuse light source on each side and a small table for the other experimental instruments. Neewer NL480 studio lights were used. The lights were angled to produce uniform lighting and to minimize the shadows cast on the backdrop by participants. Tripods with the Vive Lighthouses were set up on the front-left and rear-right edges of the backdrop. The overhead lights in the room were turned off during experimentation to reduce shadows.

Digital Reconstruction

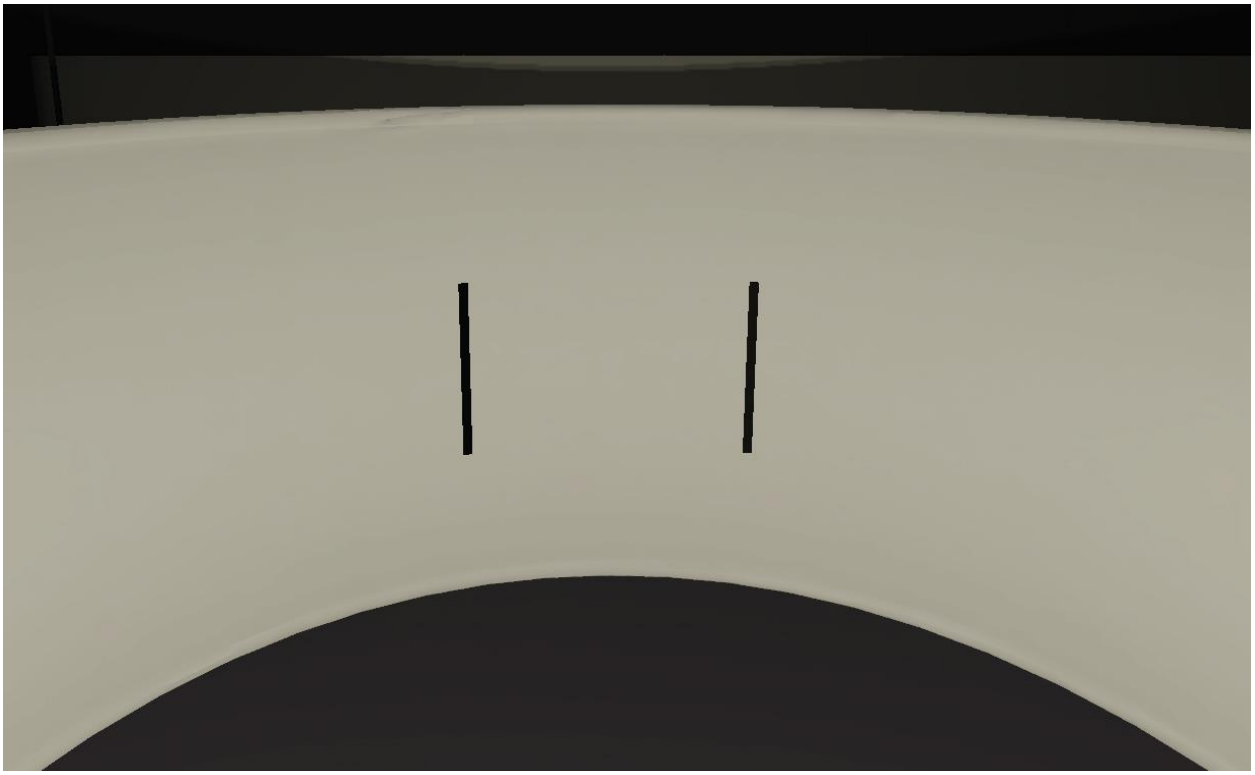

Figure 3. Digital reconstruction with gaze targets placed 32 degrees apart.

The digital reconstruction of the backdrop apparatus consisted of a 3D polygon model created to the same specifications as the physical construction. A digital model of the surrounding area was created to scale. The models were used to create a scene in Unity 2018 visually and spatially similar to the physical construction. Lighting conditions were also replicated.

The room containing the physical construction was dimensioned and modeled in Autodesk Maya, focusing on the large and defining features of the space. The colors of the walls, floor, gaze targets, and backdrop were matched by eye. Models of the tripods and Vive Lighthouses were included in the scene.

The scene was lit using area lights and baked global illumination. Lighting was baked to textures using the Enlighten light baking system in Unity. A Tektronix J16 Photometer was used to adjust the light intensity of the virtual scene until the intensity of light emitted from the Vive lenses was within the range measured when lighting the physical construction, 0.15 µ watts/cm^2 -

0.21 μ watts/cm^2. Light color was judged by eye. The disparity in light color between figures is due to the white balance of the camera used to photograph the physical construction.

Within the digital reconstruction, the spacing of the gaze targets was controlled by software. They were equal in size to those of the physical construction. Scene structure, lighting, and alignment of the gaze targets between conditions was confirmed by comparing views while sitting in the apparatus.

Measurement Devices

Two measurement devices were constructed for this experiment. An HTC Vive was internally equipped with video cameras for recording eye movements during the VR condition. A pair of headphones was equipped with identical cameras and a Vive tracking puck for head tracking. Both devices were worn during the VR condition, though the headphone cameras were only active during the direct viewing condition. The tracking puck was used in both conditions to eliminate hardware arrangement as a variable and to simplify the testing application. Onboard microcomputers recorded video of the eyes to a microSD card then transferred it to the testing computer at the end of the treatment or condition. Screen-recording software was used on the testing computer to capture the images displayed through the HMD. These video sources were synchronized by a flash cue, a solid white frame displayed for one second in the HMD which, in turn, brightly illuminated the camera recordings. By synchronizing the two recordings, eye movements could be placed in the context of both what was being viewed and any synchronous head motion. While video of only one eye was necessary for blink monitoring, recording of saccadic eye movements benefitted from a video feed of each eye. Redundancy also proved useful in the event of hardware failure.

Figure 4. Both wearable measuring apparatuses as worn during the VR condition

Headphone-Mounted Cameras and Vive Tracking Puck

For the direct viewing condition, two cameras were mounted protruding forward from a pair of headphones, one pointed at each eye. A Vive tracking puck was mounted atop the headphones for the purpose of tracking head rotation. This tracker was used to record orientation data in both direct and VR viewing conditions. The tracker's local forward vector was projected to the horizontal plane then normalized. The angle between this vector and the apparatus center line was calculated such that rotations to the left resulted in negative values and rotations to the right yielded positive values.

The headphones also served to deliver pre-recorded voice instructions throughout the experiment. Prerecorded instructions were used to eliminate variability in the tone of the instructions. Such variability could have led to mixed emotional responses to the props, increasing variability in blink patterns. The headphones were plugged into the 1/8th inch jack on the Vive. A microphone was also hooked up to the computer running the testing application so that the investigator could talk to the participants through the headphones if needed. Communication using the microphone was primarily done during apparatus setup and did not interfere during the trials.

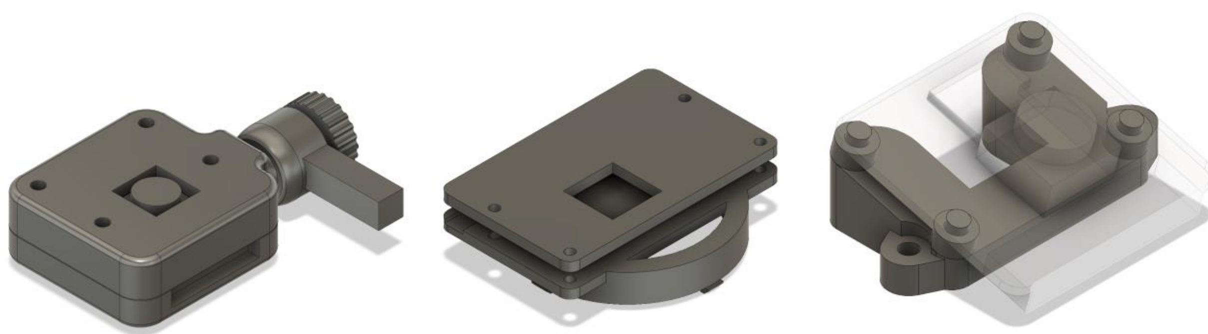

Figure 5. (Left) CAD model of camera housing and locking ball and socket joint. (Center) Raspberry Pi Zero W housing designed to mount on headphones. (Right) The wedge shaped camera mount for use with the HTC Vive.

Mounting the cameras to the subject's head during the direct viewing condition required a solution that was adjustable but would not lose alignment when handled. The headphones provided the base for custom mounting solution. Square brass extrusions were used as arms extending forward from the ear cups with a camera mounted on the end of each. Structural joints were designed in Autodesk Fusion 360 then 3D printed on a Prusa i3 MK3s. To allow for adjustability, ball and socket joints were used to attach the camera housings to the camera arms. Once oriented correctly, the ball and socket joint could be held in place by tightening a threaded knob. The housings for the Raspberry Pi Zeros were designed to clip into the existing structure of the headphones and clamp down on the brass arms. The arms could be extended or retracted by loosening the screws of these housings.

Vive-Mounted Cameras

3D printed mounts were used to secure the cameras inside of the Vive. The tight space and lack of features to attach the mounts to led to a mount design with limited adjustability. The camera mounts were solid wedge-shapes which angled the cameras toward the eyes. The mounts were held to the walls of the Vive with double-sided adhesive strips. A 15 degree wedge angle was found suitable to align the cameras with most participants' eyes.

Each camera required its own Raspberry Pi microcomputer as a controller. However, the hardware size required they be mounted externally. Velcro was added to the head strap pivot posts so that the microcomputers could be easily attached and removed. The video ribbon cable was then run from the Raspberry Pi, through the metal strap ring, under the foam face pad, and into the camera module. Power cables for the microcomputers were run along the top strap with the Vive cables.

Infrared sensitive cameras were initially chosen so that IR ring lights could be used to light the faces of participants without adding distracting visible light sources to their visual field. However, it was discovered in initial testing that the screen of the Vive provided enough illumination on its own. Therefore, the ring light was omitted to eliminate additional wiring and camera mount limitations.

Raspberry Pi Camera Controller Setup

The camera hardware used to capture video of participants' eyes consisted of Raspi NoIR Camera v2 modules, each controlled by an attached Raspberry Pi Zero W. The small form factor of this hardware allowed the cameras to be mounted on the interior of the HTC Vive used in testing and limited the weight added to the headset. The Wi-Fi capabilities of the Raspberry Pi Zero W were used to receive remote commands from the testing application and to send video data from the cameras to the test computer wirelessly.

Recording commands were coded in Python and stored on the Pi Zero. A preview streaming feature was also coded in Python to help the investigator align cameras when fitting participants with the recording apparatus. A script on the Pi Zero recorded the video stream to a network socket and a separate script on the testing computer read the stream into VLC media player. MP4 Box was installed on the Pi Zero to handle MP4 encoding before video files were downloaded from the Pi to the testing computer. The cameras were scripted to shoot at 40 frames per second. This frequency was selected due to a hardware constraint. The Pi Camera v2 modules can only capture their full field of view at or below 40fps. This capture rate was found to be acceptable by the findings of Tsubota et al. (1996).

The Pi Zeros were set up using a common image containing the prepared scripts and the required settings and software. They were then given unique static local IP addresses on a wireless router. These static IPs addresses were then used in configuring the communication code of the testing applications.

During testing, the recording scripts were executed remotely from the testing computer via SSH. Once testing was complete, MP4 Box was executed via SSH, and the resulting video files transferred over Wi-Fi via SFTP. SSH and SFTP requests were generated and sent from the testing application using the Renaissance Computing Institute (RENCI) SSH.NET library.

Data collection methods

Participants completed a series of gaze changes under two different conditions. This task was completed three times while wearing an HTC Vive, and three times while viewing a physical apparatus directly. Within each viewing condition there were two stimuli markers placed at varying separations throughout the experiment. These served as gaze targets. When prompted, participants turned to look from one target to the other. Such gaze changes happened 40 times sequentially for each different stimulus spacing. Three different spacing values were used: 15 degrees, 32 degrees, and 100 degrees. Viewing condition and separation order was determined by a crossover model to control for any order effects.

Preprocessing

Prior to their arrival, participants were assigned to a group which would determine their order of treatments. The gaze targets were placed at the appropriate separation for their first set of direct viewing trials before the participants' arrival. Participants were told that their eye movements were being recorded. Though, the kind of movements that were being examined was left vague. Participants were instructed to perform the task naturally in whatever way was most comfortable. This language was chosen to permit head movements without explicitly encouraging them. They were told that they were going to be looking back and forth between two lines on command. The physical construction was set up with gaze targets to offer a visual aid accompanying this instruction.

After eligibility screening and general instruction, participants were told which condition they would be completing first. They were then seated in the apparatus and fitted with the associated measurement devices. The cameras were aligned, and testing sequence was set by entering their group number into the testing software. Once setup was complete, participants started either the direct viewing process or VR process, depending on their group.

Direct Viewing Process

For the direct viewing condition, participants were fitted with the headphone-mounted cameras and Vive puck. First, a stable comfortable fit had to be ensured. Then the cameras had to be activated and aligned. This was done by running the preview stream script from the testing application's interface, and adjusting the ball and socket joints of the camera mounts. Once fitted, the participant's group number was entered into the testing application, and the test started.

From this point on, all instruction was given via pre-recorded messages. A recording reiterated the instructions that the participant was to look between gaze targets when prompted. Once they confirmed the instructions were understood, they were instructed to look at either the left or the right line. Which line they started with was randomized. After a brief period, they were instructed to look at the other line. Forty gaze changes were performed before the angle of separation between the lines was changed. The timing of gaze changes was randomized to prevent predictable rhythms. Time between instructions was either 1.625 seconds, 2.5 seconds, or 3.375 seconds. Each interval was used thirteen times per trial set, with one random interval being used one additional time.

The line separation was changed manually by the experimenter. Gaze targets were unpinned then repined in new locations based on the participant's group. While the targets were being moved, the Raspberry Pi camera controllers would encode the recorded videos and upload them to the testing computer. Fetching the data throughout the experiment helped reduce wait time between conditions and helped catch data loss errors early. Once the gaze targets had been changed, the experiment and video capture would be resumed for another forty gaze changes. Three sets of forty gaze changes were performed in the direct viewing condition, each with a different target separation; 15, 32, or 100 degrees.

VR Process

For the HMD viewing condition, participants were fitted with the HTC Vive and headphone-mounted Vive tracking puck. Then camera alignment and tracker output were both verified. Once this setup process was complete, the participant's group number was entered into the testing application, and the test started.

As in the direct viewing condition, all further instruction was given via pre-recorded messages. The instructions that the participant was to look between gaze targets when prompted were reiterated. Once they confirmed the instructions were understood, the gaze targets moved into place and they were instructed to look at one of the lines. Which line they started with was randomized. After a brief period, they were instructed to look at the other line. Forty gaze changes were performed before the angle of separation between the lines was changed. Gaze change intervals were randomized using the same methods as in the direct viewing condition. Because gaze targets were controlled by software, they could be moved with no down time. Therefore, video for the VR condition was recorded as on continuous clip and downloaded to the test computer after all trial sets were complete.

Analysis

Orientation Data Processing

Positional data collected from the head tracker was quite extensive, with about 60 data points being collected each second. A C# script was written to extract key data points for each gaze change. The script read through the records and found the minimum and maximum rotations over the course of the trial, then used those to calculate the change in orientation. Once all delta values were calculated for a forty trial set, the average, sample variance, sample standard deviation, minimum, maximum, median, and quartiles were calculated.

Blink Data Extraction

Blink information was extracted from video recordings manually using Adobe After Effects and Lloyd Alvarez's Marker Batch Editor. After Effects allowed the video to be examined frame by frame when needed, though most blinks were easily found scrubbing through the footage at faster rate. First, all footage of a given session was composited into a single composition and synchronized. Footage between cameras started at the same time, and were thus easily synched. Footage from the Vive cameras was synched with the screen capture footage by aligning the frames in which the view turned white with those where the camera footage was blown out. Having multiple views side-by-side helped provide context and limit ambiguity when judging the qualities of blinks.

After Effects includes a marker feature that allows comments to be added to clips at specific timestamps. For each blink, a marker was placed on the frame where the eyelid was most closed. Only one marker was used per blink. Blinks were classified as either coupled or independent and either full or partial. Coupled blinks were those which either accompanied a saccade or occurred within 100ms, or 4 video frames, of a one (Fogarty & Stern, 1989). Partial blinks were those in which the eyelids did not fully cover the iris. These classifications were added to the comments section of the corresponding marker in a comma-separated format. Once all blinks in a session were marked and commented, the marker timestamps and classifications were exported to a .csv file using the Marker Batch Editor. Once the blink data was in spreadsheet form, total blinks per treatment, the percentage of full blinks, and the percentage of coupled blinks were calculated. Temporal information was also extracted: mean, median, minimum, and maximum time between blinks were all calculated. Sample standard deviation was also calculated for time between blinks.

Statistical Methods

Analysis of Variance (ANOVA) was used to conduct F-tests, at $\alpha = 0.05$, to determine the significance of predictors. The General Linear Model (GLM) procedure in SAS was used to account for missing, corrupt, or naturally unbalanced data points. A backward elimination strategy was used to determine the predictors to be included in the final model. That is to say, multiple ANOVAs were run, starting with the full model with all predictors, and eliminating the least significant predictor until all remaining predictors were found to be significant. Predictors included in the full model were: subject, view condition, angle of separation between targets, order of treatment, and the interaction between view condition and angle between targets. Type II Sums of Squares calculations were used to compute F-values for backward elimination. That is, F-values were based upon the variability accounted for by each predictor when it was added to the model last.

A power analysis was run for the model, using a significance level of 0.05 and an effect size of 0.5. For the sample size used in this study, the power values for view, angle, and interaction effects were calculated to be 0.30, 0.21, and 0.13, respectively.

Table 1. Power analysis of the experimental model at different sample sizes

Sample Size	View Effect Power	Angle Effect Power	Interaction Effect Power
6	0.30	0.21	0.13
12	0.55	0.40	0.22
18	0.73	0.55	0.32
24	0.84	0.68	0.40
30	0.91	0.78	0.49
36	0.95	0.85	0.56

Blink Rate

In order to determine whether view condition affected overall blink rate, an ANOVA was run with the observed blink rate used as the dependent variable. Because all treatments were of equal temporal length, total number of blinks per treatment was the value used in analysis. This equates to number of blinks per two minutes and thirty seconds. Once the blink count was tallied for each treatment, the backward elimination strategy was used with the ANOVA to build the best fitting model. GLM was used here because a camera script bug lead to a loss of data for one treatment of one participant.

Coupled Blinks

It has been previously observed that the magnitude of a gaze shift has significant effects on the likelihood of a coupled blink (Fogarty & Stern, 1989). In order to determine whether viewing condition has a main effect or causes an interaction, the total number of coupled blinks in a given treatment was used as the dependent variable in the ANOVA. GLM was used here due to the lost data point mentioned above.

Inter-Blink Period

For each sequential pair of blinks, the inter-blink period (IBP) was calculated. The total number of IBPs calculated was 788. The ANOVA was backward elimination strategy was then used to find any predictors with significant effects on IBP. GLM was used here due to the naturally unbalanced data.

Facing Direction

The magnitude of saccades was analyzed indirectly, utilizing the assumption that the difference between the angle of gaze target separation and the angle of head rotation would indicate the rotation of the ocular orbit required to acquire fixation. Therefore, to gain insight into whether viewing condition had an effect on saccade amplitude, the change in head rotation was used as the dependent variable in the ANOVA model. The total number of angle delta values used was 1409. GLM was used here because there was interference with the tracking system during one participant's testing session and the affected data points were removed.

Summary

In order to predict the risk of dry eye due to head-mounted display use, an experiment was run comparing spontaneous eye blink rates across VR and direct viewing conditions. This was done in a controlled environment using custom camera apparatuses and manual video analysis. A balanced crossover model was used to account for order effects and to allow within subject analysis.

Other variables were measured to provide deeper insight into the relation between gaze changes, blink patterns, and HMD use. The number of gaze evoked blinks were extracted from video footage and compared across viewing conditions. Inter-blink period was calculated for each pair of sequential blinks. The change in head rotation was tracked for each gaze change. The measured variables were evaluated against a set of predictors using backwards elimination in an ANOVA model. Significance of predictors was determined via F-tests. Seven male subjects participated in the study, though a miscommunication with one led to only six being included in the analysis.

CHAPTER 4. RESULTS

Total Blink Rate

Table 2. F-Values from ANOVA backward elimination for blink rate

	F1	Pr >F1	F2	Pr >F2	F3	Pr >F3	F4	Pr >F4	F5	Pr >F5
Subject	2.06	0.1627	2.13	0.1553	2.13	0.1553	2.08	0.1594	2.01	0.1656
Angle	1.89	0.1707	1.96	0.1597	2.02	0.1512	2.00	0.1524		
View*Angle	1.18	0.3238	1.22	0.3110	1.12	0.3595				
View	0.88	0.3560	0.91	0.3481						
Period	0.03	0.8684								

The first research question of this study was: Is there a difference in blink rate between direct viewing and HMD use? The null hypothesis was that there is no difference in blink rate between viewing conditions. The findings of this study fail to reject that null hypothesis.

The process of ANOVA backward elimination for analysis of blink rate predictors is shown in . First the full model was evaluated, yielding the F-valued shown in the F1 column. The least significant predictor was then selected for elimination from the model. Period, the order in which a treatment was given, was eliminated first. The ANOVA was ran again without Period, yielding the F-values in the F2 column. Elimination of predictors continued in this way. The next least significant predictor was the viewing condition. Its elimination from the model led to the conclusion that the null hypothesis could not be rejected. Continuing the backward elimination process showed that no predictor was found to be significant. This could be a result of the lack of power resulting from the small subject pool, the high variability of blink rates as seen in the literature, or a combination of the two.

Coupled Blinks

Table 3. F-Values from ANOVA backward elimination for coupled blinks

	F1	Pr > F1	F2	Pr > F2	F3	Pr > F3	F4	Pr > F4
Angle	24.88	<.0001	25.55	<.0001	25.31	<.0001	24.97	<.0001
Subject	8.83	0.0062	9.04	0.0055	9.04	0.0055	9.08	0.0051
View*Angle	1.19	0.3187	1.23	0.3066	1.14	0.3506		
View	0.92	0.3472	0.95	0.3384				
Period	0.32	0.5768						

The second research question posed by this study was: Is there a difference in the likelihood of blinks occurring concurrent with gaze shifts between direct viewing and HMD viewing conditions? The null hypothesis was that there is no difference in the likelihood of gaze evoked blinks between viewing conditions. The findings of this study fail to reject that null hypothesis.

The process of ANOVA backward elimination for analysis of gaze evoked blink predictors is shown in , starting with the F-values of the full model in the F1 column. Period, or treatment order, was eliminated from the model as the least significant predictor, indicating that order effects were properly controlled. Viewing condition was eliminated as the next least significant predictor, showing that HMD usage had no significant effect on whether a gaze change prompted a blink. This led to the failure to reject the null hypothesis. Finally, the view-separation interaction was eliminated, yielding the final model. The final model shows the significant predictors of gaze evoked blinks to be the angle between gaze targets, as similarly shown by Fogarty and Stern (1989), and subject.

Head Rotation

Table 4. F-Values from ANOVA backward elimination for head rotation

	F1	Pr > F1	F2	Pr > F2
Angle	2635.39	<.0001	2634.07	<.0001
Subject	424.83	<.0001	422.08	<.0001
View	192.13	<.0001	193.13	<.0001
View*Angle	132.10	<.0001	131.41	<.0001
Period	3.26	0.0711		

Changes in head rotation were used as indirect measures of saccades to determine whether saccade dynamics were affected by viewing condition. The null hypothesis was that viewing condition would not affect saccade dynamics. That null hypothesis has been rejected. Starting with the full model, period was identified as eliminable. The remaining predictors were all found to be significant. The significance of viewing condition led to the rejection of the null hypothesis.

The significance of the angle of separation between gaze targets is obvious; larger separations required more head rotation. Subject effects can be seen by selecting a treatment and plotting the subjects alongside each other, as in Figure 6. This shows that some moved their head less than the others, or not at all.

Figure 6 also reveals that, due to the small sample size, an order effect has been conflated with the subject effect. Participants C60 completed the direct viewing condition first; with a separation order of 32, 15, then 100 degrees. The 100 degree treatment is possible to complete without head rotation in the direct viewing condition, but not the VR condition. The head rotations were also very small in the 32 and 15 degree conditions across all participants. Therefore, it is likely that participant C60 was primed for no head rotation by not needing to make any head rotations up to that point.

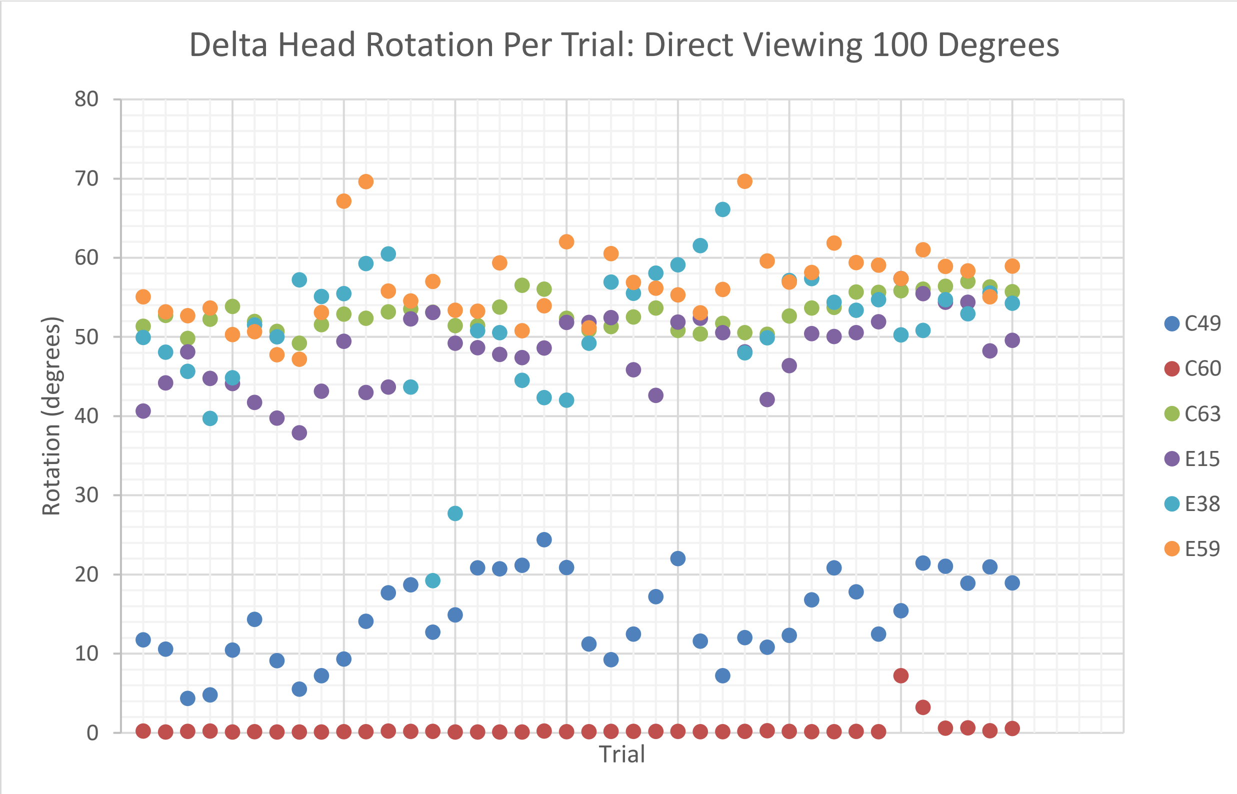

Figure 6. Change in head rotation plotted for each trial in the 100 degree direct viewing treatment shows differences between the behaviors of subjects

The view effect can be seen clearly just by looking at the aggregate data table in the appendix. The VR condition consistently yielded higher rotation values than the direct condition. The exception is participant E59, who experienced substantial tracking interference. This interference was groomed from the data for the ANOVA, but was present when generating the aggregate data table.

The interaction effects can be seen quite clearly in the interaction plot in Figure 7. The slope of the 15 and 32 degree lines are nearly horizontal and parallel. But, the 100 degree line in sloped dramatically. This shows that the view effect is modulated by the separation angle. Trials at smaller separations could be completed by saccade only. Any head rotation arose as a means of habit or comfort. However, the 100 degree separation pushed the gaze targets outside the field of view of the HMD. This showed that larger gaze changes were more affected by the limitations imposed by the HMD.

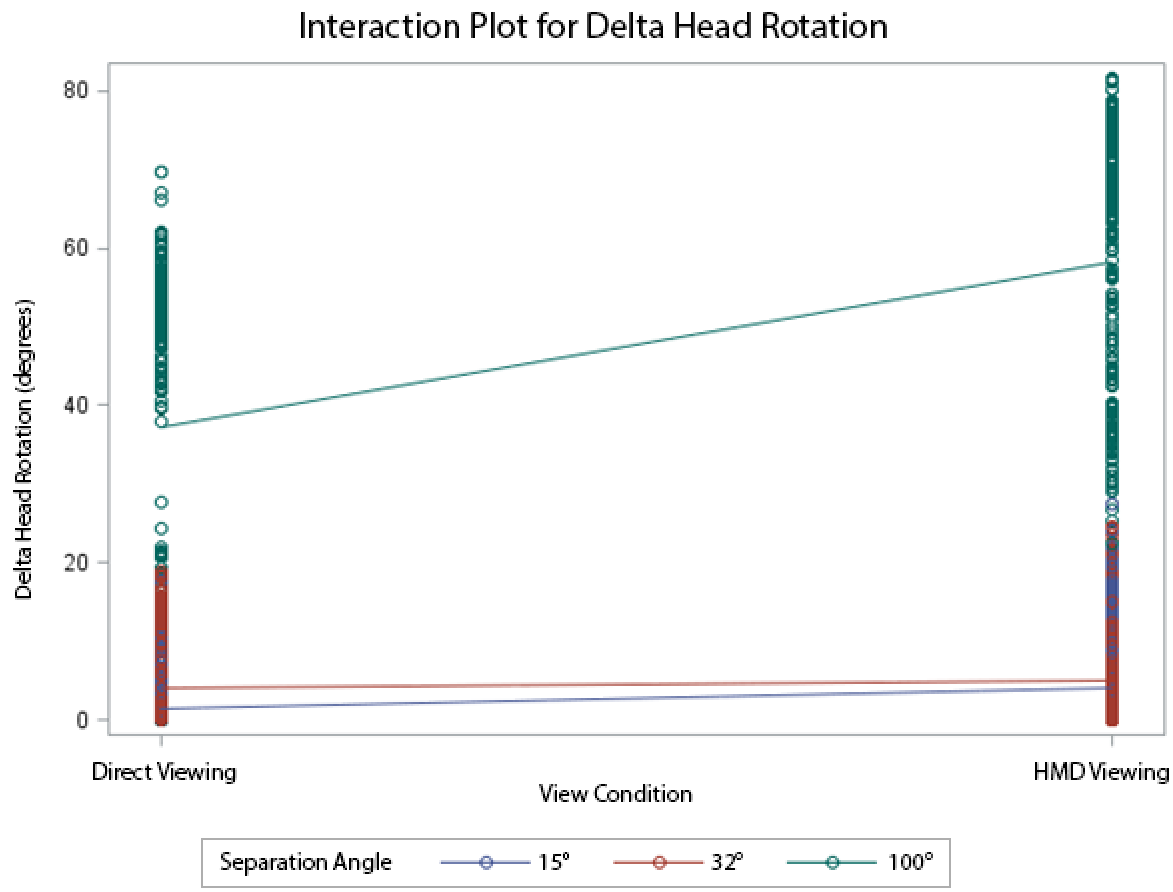

Figure 7. The interaction plot for the view*angle effect on head rotation

Inter-Blink Period

Table 5. F-Values from ANOVA backward elimination for inter-blink period

	F1	Pr > F1	F2	Pr > F2	F3	Pr > F3
Subject	11.18	0.0009	11.18	0.0009	10.76	0.0011
Angle	8.26	0.0003	8.51	0.0002	8.33	0.0003
View*Angle	7.76	0.0005	5.19	0.0015	4.95	0.0021
Period	1.92	0.1659	1.92	0.1659		
View	0.05	0.8203				

Further analysis was run on the inter-blink period. Backward elimination showed that subject, separation, and the interaction between separation and view condition were all significant. The relations between IBP and separation, and IBP and the interaction are likely the fault of the experimental design. As seen in the analysis of coupled blinks and overall blink rate, separation was a strong predictor of coupled blinks but was insignificant to total number of blinks. This indicates that blinks were timed to concur with gaze changes at higher separations, but these gaze evoked blinks were not additive to the total number of blinks. They were only shifted temporally to align with saccades. This lends validation to the thesis that blinks are subconsciously timed to concur with other visual disruptions to maximize information throughput. In the context of this experiment, however, it means that the periodic gaze shifts homogenized IBP, making blinking more rhythmic. This was further illustrated by calculating the standard deviations of IBP per treatment. The median standard deviation for treatments at 15, 32, and 100 degrees were 7.57, 12.33, and 5.34, respectively.

Summary

The findings showed that it was possible to evoke blinks by prompting gaze changes in head mounted displays. These gaze evoked blinks did not, however, have a significant effect on overall blink rate. Rather, blinks tended to be timed to the gaze changes, homogenizing their frequency. Further, the magnitude of the gaze change was the most significant predictor of gaze evoked blinks, with only the largest reliably evoking blinks. HMD use was an insignificant factor in both total number of blinks and gaze evoked blinks.

Head rotation was shown to be significantly affected by all predictors. The angle of separation was the most significant effect. Analysis showed that the degree of head rotation was greater in the VR viewing condition. An interaction between the angle effect and the view effect was also discovered, showing that the view effect was increased in the presence of wide angles of separation. While the statistical analysis did not find any significant order effect, the data was interpreted to indicate an order effect may have been conflated with the subject effect.

Full ANOVA tables and aggregate data tables have been included in the Appendix.

CHAPTER 5. DISCUSSION AND CONCLUSION

Conclusions

The general conclusion of this study is that head mounted displays do not have a significant impact on blink rate or gaze evoked blinks. Therefore, HMD technology poses no significant risk of dry eye in terms of blink rate. However, other risk factors have yet to be examined. HMDs are designed for forward gaze, so palpebral aperture could be a significant dry eye factor in VR. Blink modulation due to level of attention will vary greatly between VR tasks. Atmospheric and thermal factors are others to consider when a display is enclosed inches from the eyes.

Further, gaze changes only affected the temporal placement of blinks, not the total number. Even with large gaze changes evoking blinks approximately every two seconds, an increase in blink rate was not observed. Therefore, the use of head movements to promote higher blink rates would be an invalid tactic. Attempts to promote gaze changes to evoke blinks would not only be ineffective, but also would introduce the risk of a repeated stress injury. That is not to say that gaze changes should be avoided. They are a key part of the immersive VR experience. But, designing VR software with the sole goal of increasing the number and frequency gaze changes is ill-advised.

HMDs were shown to have an effect on gaze dynamics. However, this effect does not seem to cascade to gaze evoked blinks. While this study did show altered gaze dynamics, it was at the level of head rotation. A study utilizing eye tracking technology would be required to explore any effects on precise saccade dynamics; such as timecourse, total magnitude, and number of saccades per gaze change. There do not appear to be any relations between these variables and dry eye.

Future Work

There is much room for further investigation in this field. The following details improvements to this experimental design, as well as some new areas of investigation.

A number of improvements could be made to data collection and handling methods. Using eye tracking software would allow for deep analysis of each saccade. Better methods of synchronization for temporal records could be used. By having multiple data sources that were all independent of one another, synchronization was a problem. Eye tracking software could solve this by consolidating log creation responsibility into a single program. Eye tracking would also allow for quantitatively measured saccades. By not relying on human analysis of footage, bigger sample sizes could be used.

This study used an environment carefully sterilized on nuisance variables to provide an analysis of HMD hardware effects. There is still a software component to the VR experience that has not been considered. A comparison of blink rate between different VR applications could prove informative. Cardona et al. (2011) ran a similar study on desktop displays.

For future studies of this kind, a different separation angles would provide a better understanding of the relationship between separation and viewing condition. The results for 15 degrees of separation and 32 degrees of separation were very similar. An angle between 32 and 100 degrees would lead to a more complete analysis. Fogarty and Stern (1989) saw effects on gaze evoked blink rate in 50 degree saccades. A better angle set would be 30, 50, and 100 degrees.

The effects of gaze shifts over a varied visual field could provide information on how visual environment affects gaze evoked blinks. Variables such as spatial frequency, luminance, color, and contrast could be explored. Such information would help explain how blinks emerge in VR applications with visually rich environments.

A possible factor that was left unexamined in this study was the effects of stereo acuity. Those who are unable to fuse false stereo images may have unobserved effects on VR studies. Future studies in VR should screen for stereo acuity with a virtual Howard-Dolman apparatus.

APPENDIX

ANOVA Backward Elimination for Blink Count

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	218.4960232	218.4960232	2.06	0.1627
period	1	2.9697577	2.9697577	0.03	0.8684
view	1	93.5465749	93.5465749	0.88	0.3560
separation	2	400.7340477	200.3670239	1.89	0.1707
view*separation	2	249.4973938	124.7486969	1.18	0.3238

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	218.3518625	218.3518625	2.13	0.1553
view	1	93.2565763	93.2565763	0.91	0.3481
separation	2	401.4134247	200.7067123	1.96	0.1597
view*separation	2	249.4258851	124.7129426	1.22	0.3110

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	218.3518625	218.3518625	2.13	0.1553
separation	2	414.2803667	207.1401833	2.02	0.1512
view*separation	3	342.6824614	114.2274871	1.12	0.3595

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	215.2345526	215.2345526	2.08	0.1594
separation	2	414.2803667	207.1401833	2.00	0.1524

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	220.8271296	220.8271296	2.01	0.1656

ANOVA Backward Elimination for Coupled Blinks

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	178.412212	178.412212	8.83	0.0062
period	1	6.452327	6.452327	0.32	0.5768
view	1	18.502407	18.502407	0.92	0.3472
separation	2	1005.774168	502.887084	24.88	<.0001
view*separation	2	48.240213	24.120106	1.19	0.3187

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	178.219293	178.219293	9.04	0.0055
view	1	18.708456	18.708456	0.95	0.3384
separation	2	1008.030216	504.015108	25.55	<.0001
view*separation	2	48.658103	24.329051	1.23	0.3066

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	178.2192932	178.2192932	9.04	0.0055
separation	2	998.2267660	499.1133830	25.31	<.0001
view*separation	3	67.3665588	22.4555196	1.14	0.3506

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	181.4845526	181.4845526	9.08	0.0051
separation	2	998.2267660	499.1133830	24.97	<.0001

ANOVA Backward Elimination for Head Rotation

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	48886.5753	48886.5753	424.83	<.0001
period	1	375.3379	375.3379	3.26	0.0711
view	1	22108.7837	22108.7837	192.13	<.0001
separation	2	606533.2764	303266.6382	2635.39	<.0001
view*separation	2	30403.0063	15201.5032	132.10	<.0001

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	48649.3168	48649.3168	422.08	<.0001
view	1	22259.7504	22259.7504	193.13	<.0001
separation	2	607206.7688	303603.3844	2634.07	<.0001
view*separation	2	30293.6059	15146.8029	131.41	<.0001

ANOVA Backward Elimination for IBP

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	1080.309665	1080.309665	11.18	0.0009
period	1	185.802501	185.802501	1.92	0.1659
view	1	4.991239	4.991239	0.05	0.8203
separation	2	1595.388797	797.694398	8.26	0.0003
view*separation	2	1499.843178	749.921589	7.76	0.0005

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	1080.309665	1080.309665	11.18	0.0009
period	1	185.802501	185.802501	1.92	0.1659
separation	2	1643.965973	821.982986	8.51	0.0002
view*separation	3	1504.834417	501.611472	5.19	0.0015

Source	DF	Type II SS	Mean Square	F Value	Pr > F
subject	1	1040.732904	1040.732904	10.76	0.0011
separation	2	1611.303966	805.651983	8.33	0.0003
view*separation	3	1435.824387	478.608129	4.95	0.0021

Aggregate Data Tables

			Blink Count					Temporal Separation (seconds)				
Subject	View	Angle	Total	Full	Full %	Coupled	Coupled %	Avg	Median	Min	Max	Std Dev
C49	Direct	15	16	15	94%	3	19%	8.48	4.24	0.53	23.78	8.7863
C49	VR	15	20	19	95%	2	10%	4.44	1.48	0.38	51.03	10.2365
C49	Direct	32	13	13	100%	2	15%	12.49	7.90	0.23	71.28	18.7844
C49	VR	32	17	16	94%	4	24%	7.69	5.00	0.55	48.55	11.2395
C49	Direct	100	40	37	93%	25	63%	3.77	3.90	1.38	7.80	1.7083
C49	VR	100	26	19	73%	20	77%	4.67	3.00	0.90	30.25	6.1451
C60	Direct	15	18	9	50%	5	28%	14.56	10.10	1.65	65.65	15.4619
C60	VR	15	16	6	38%	8	50%	9.51	5.15	0.95	45.85	11.1584
C60	Direct	32	25	11	44%	5	20%	10.92	5.75	0.97	68.95	15.0781
C60	VR	32	15	1	7%	4	27%	10.76	8.68	0.85	48.93	13.4187
C60	Direct	100	26	16	62%	16	62%	8.90	4.33	1.10	57.90	13.2112
C60	VR	100	35	22	63%	30	86%	3.77	1.98	0.30	24.05	5.0196
C63	Direct	15	32	14	44%	1	3%	5.41	4.92	2.10	11.13	2.1743
C63	VR	15	22	5	23%	4	18%	7.36	5.83	0.65	29.88	6.3537
C63	Direct	32	32	19	59%	8	25%	5.38	4.00	2.60	11.28	2.5299
C63	VR	32	19	1	5%	7	37%	9.00	5.65	0.38	27.53	7.7093
C63	Direct	100	20	11	55%	9	45%	8.70	8.04	1.45	17.75	5.3395
C63	VR	100	24	3	13%	18	75%	6.66	6.94	0.35	14.83	3.7423
E15	Direct	15	25	25	100%	6	24%	7.16	4.63	0.52	21.43	6.3295
E15	VR	15	8	8	100%	2	25%	9.86	4.60	0.70	39.73	11.9051
E15	Direct	32	29	28	97%	6	21%	5.80	3.60	0.50	24.20	5.3451
E15	VR	32	11	10	91%	1	9%	14.32	11.03	0.98	35.13	10.7784
E15	Direct	100	37	35	95%	10	27%	4.71	3.00	0.65	23.73	5.1196
E15	VR	100										
E15 Notes:	Last third of VR video cut off, no observations for 100 degree treatment.											
E38	Direct	15	15	9	60%	2	13%	9.39	10.56	0.13	23.85	7.2587
E38	VR	15	56	45	80%	8	14%	3.14	1.73	0.13	14.33	3.9639
E38	Direct	32	11	2	18%	3	27%	15.96	3.00	0.13	105.60	32.5698
E38	VR	32	3	1	33%	0	0%	28.93	37.03	0.70	62.03	27.3207
E38	Direct	100	15	4	27%	15	100%	17.32	12.15	4.33	75.28	18.1876
E38	VR	100	18	8	44%	17	94%	8.83	6.88	0.15	40.58	9.8699
E59	Direct	15	14	14	100%	1	7%	10.79	10.90	0.43	23.38	7.8828
E59	VR	15	19	17	89%	3	16%	8.16	6.21	0.23	21.93	4.8916
E59	Direct	32	16	16	100%	2	13%	10.15	9.81	3.68	18.18	4.1215
E59	VR	32	5	5	100%	2	40%	26.20	26.75	8.08	43.43	16.4847
E59	Direct	100	21	20	95%	4	19%	7.98	7.45	0.95	14.08	3.9968
E59	VR	100	10	10	100%	4	40%	15.63	14.25	7.72	33.00	7.7877
Average	Direct	15	20.00	14.33	75%	3.00	16%	9.30				
Average	VR	15	23.50	16.67	71%	4.50	22%	7.08				
Average	Direct	32	21.00	14.83	70%	4.33	20%	10.12				
Average	VR	32	11.67	5.67	55%	3.00	23%	16.15				
Average	Direct	100	26.50	20.50	71%	13.17	53%	8.56				
Average	VR	100	22.60	12.40	59%	17.80	74%	7.91				

			Head Tracking Delta Rotation (degrees)								
Subject	View	Angle	Avg	Sum of Sqr	Variance	Std Dev	Min	Max	Q1	Q3	Median
C49	Direct	15	0.52	4.6509	0.1193	0.3453	0.15	1.97	0.34	0.59	0.45
C49	VR	15	0.63	9.8569	0.2527	0.5027	0.22	2.92	0.33	0.74	0.48
C49	Direct	32	0.38	8.6371	0.2215	0.4706	0.09	2.92	0.17	0.39	0.25
C49	VR	32	1.23	131.1242	3.3622	1.8336	0.16	9.10	0.23	1.64	0.45
C49	Direct	100	14.61	1143.6760	29.3250	5.4153	4.35	24.38	10.57	20.70	14.20
C49	VR	100	41.87	1995.4170	51.1645	7.1529	30.33	56.50	35.76	46.09	42.71
C60	Direct	15	0.20	0.1900	0.0049	0.0698	0.10	0.41	0.15	0.25	0.17
C60	VR	15	0.70	75.4200	1.9338	1.3906	0.09	7.90	0.12	0.59	0.20
C60	Direct	32	0.44	14.9732	0.3839	0.6196	0.13	4.14	0.25	0.40	0.32
C60	VR	32	1.22	488.2902	12.5203	3.5384	0.09	18.29	0.13	0.39	0.16
C60	Direct	100	0.45	56.4008	1.4462	1.2026	0.11	7.22	0.13	0.23	0.18
C60	VR	100	34.88	1377.1200	35.3108	5.9423	24.26	52.63	30.33	38.20	34.20
C63	Direct	15	2.13	164.2855	4.2124	2.0524	0.24	7.52	0.37	4.03	1.02
C63	VR	15	3.83	341.3472	8.7525	2.9585	0.42	10.19	0.88	6.15	3.99
C63	Direct	32	13.20	147.5791	3.7841	1.9453	8.97	17.20	11.77	14.72	13.40
C63	VR	32	18.28	479.7494	12.3013	3.5073	10.98	24.26	15.59	21.40	18.58
C63	Direct	100	53.02	177.4135	4.5491	2.1329	49.22	57.01	51.37	55.63	52.69
C63	VR	100	75.39	426.9912	10.9485	3.3089	67.18	81.36	72.90	78.28	75.62
E15	Direct	15	0.49	15.0092	0.3848	0.6204	0.15	3.07	0.20	0.57	0.26
E15	VR	15	1.05	140.8568	3.6117	1.9005	0.18	10.81	0.32	0.73	0.39
E15	Direct	32	1.17	47.0713	1.2070	1.0986	0.14	4.04	0.36	1.79	0.76
E15	VR	32	1.02	54.5057	1.3976	1.1822	0.18	5.47	0.31	1.39	0.42
E15	Direct	100	48.14	839.3845	21.5227	4.6393	37.89	57.37	44.13	51.87	48.62
E15	VR	100	66.80	1444.6990	37.0436	6.0863	56.02	78.37	61.76	71.36	66.46
E38	Direct	15	0.76	6.5755	0.1686	0.4106	0.27	1.98	0.51	0.94	0.60
E38	VR	15	3.34	367.0434	9.4114	3.0678	0.39	13.76	1.37	4.64	2.05
E38	Direct	32	0.99	91.1789	2.3379	1.5290	0.36	10.10	0.51	0.92	0.66
E38	VR	32	3.07	1049.7850	26.9176	5.1882	0.40	22.46	0.56	2.91	0.94
E38	Direct	100	50.95	2922.9420	74.9472	8.6572	19.24	66.09	48.01	56.93	52.22
E38	VR	100	61.07	3385.1190	86.7979	9.3165	43.95	78.45	52.70	68.30	61.65
E59	Direct	15	18.15	15909.5300	407.9367	20.1974	0.00	73.39	4.91	30.31	9.02
E59	VR	15	17.82	6574.1420	168.5677	12.9834	0.00	74.62	13.74	17.64	15.59
E59	Direct	32	23.62	57422.5000	1472.3720	38.3715	1.49	205.31	5.85	18.32	12.24
E59	VR	32	5.34	954.2518	24.4680	4.9465	0.00	24.51	1.84	7.45	3.98
E59	Direct	100	56.59	996.6634	25.5555	5.0552	47.19	69.66	53.16	59.33	56.08
E59	VR	100	71.11	10379.3300	266.1368	16.3137	22.58	156.47	66.14	74.06	69.24
E59 Notes:	Tracker issues lead to high error.										
Average	Direct	15	3.71								
Average	VR	15	4.56								
Average	Direct	32	6.63								
Average	VR	32	5.03								
Average	Direct	100	37.29								
Average	VR	100	58.52								

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