DIGITAL EYE STRAIN

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Thesis abstract

Digital eye strain (DES) encompasses a variety of visual and ocular symptoms that arise due to the prolonged use of digital devices. The 2023 Tear Film Ocular Surface (TFOS) Lifestyle report defined DES as “the development or exacerbation of recurrent ocular symptoms and / or signs related specifically to digital device screen viewing”. Ocular symptoms include blurred vision, diplopia, difficulty focussing at near, asthenopia, headache, tired and sore eyes, dryness, burning, tearing and irritation.

A clinical evaluation of the Bernell pocket critical flicker-fusion frequency (CFF) tester was undertaken to assess its value in the field of CFF research. The device was found to have good intraexaminer repeatability and reproducibility and was used in subsequent investigations within this thesis.

Two of the experimental chapters measured the impact of a novel, laptop privacy screen filter on individuals with DES. The findings showed that the privacy screen filter did not reduce DES symptoms after an intense 30- and 60-minute task.

The relationship between DES symptoms, productivity, and work accuracy has previously been unclear. As shown in this thesis, symptoms increased with task duration in individuals with DES, at a faster rate for more demanding tasks. This was associated with a reduction in productivity, but not in work accuracy.

A moderately positive relationship was observed between the Computer Vision Syndrome (CVS-Q), Ocular Surface Disease Index (OSDI) and the revised Convergence Insufficiency Symptom Survey (CISS) questionnaires indicating that individuals with DES are also likely to be symptomatic of dry eye disease (DED) and / or a binocular vision anomaly (BVA).

Finally, the author of the thesis commenced the process of developing a new, validated DES questionnaire that, once completed, can be used globally. A comprehensive literature review, focus group studies and development of questionnaire items were all undertaken within the scope of this thesis.

Keywords: Optometry, Digital Eye Strain, Computer Vision Syndrome, Dry Eye Disease, Symptoms

Dedication

“Most assuredly, I say to you, he who hears My word and believes in Him who sent Me has everlasting life, and shall not come into judgment, but has passed from death into life” (John 5:24).

To my husband, Jamie Beeson, and my parents, Annette and Jeffrey Edwards, thank you for your continuous love, support, and encouragement. I love you all very much.

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I would like to express my sincere thanks to my supervisors, Professor James Wolffsohn and Dr Amy Sheppard for their support and guidance over the last three years. It has been a pleasure to complete my PhD under your expert supervision.

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List of Abbreviations

α	Cronbach's alpha
AMOLED	Active-Matrix Organic Light-Emitting Diode
AR	Anti-reflection
BAK	Benzalkonium chloride
BSV	Binocular single vision
BVA	Binocular vision anomaly
CCFL	Cold-cathode fluorescent lamp
cd/m²	Candelas per square meter
CEF	Contrast-enhancing filter
CFF	Critical flicker-fusion frequency
CISS	The revised Convergence Insufficiency Symptoms Survey
CMC	Carboxymethylcellulose
cpd	Cycles per degree
CR	Coefficient of repeatability
CRT	Cathode-ray tube
CSF	Contrast sensitivity function
CV	Coefficient of variation
CVS	Computer vision syndrome
CVS-F3	Computer Vision Syndrome: Form 3 Questionnaire
CVS-Q	Computer Vision Syndrome Questionnaire
CVSS17	Computer-Vision Symptom Scale
D	Dioptres
DED	Dry eye disease
DEQ-5	5-item Dry Eye Questionnaire
DES	Digital eye strain
DESQ	Digital Eye Strain Questionnaire
DESRIL-27	Digital Eye Strain and Risk Level Questionnaire
DMN	Default mode network
DSE	Display screen equipment
Δ	Prism dioptres

EFAs	Essential fatty acids
EMG	Electromyography
EOG	Electrooculography
EPD	Electrophoretic display
FD	Fixation disparity
FHD	Full High-Definition
FOMO	Fear of missing out
g	Grams
GB	Gigabytes
HPMC	Hydroxypropyl methylcellulose
HSE	Health and Safety Executive
Hz	Hertz
ICC	Intraclass Correlation Coefficient
IPL	Intense pulsed light
IPS	In-plane switching
kB	Kilobytes
kg	Kilograms
K5M	Oculus Keratograph 5M topographer
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LGN	Lateral geniculate nucleus
LLT	Lipid layer thickness
LOA	Limits of Agreement
LPS	Levator palpebrae superioris
LWE	Lid wiper epitheliopathy
M	Magnocellular
MCS	Method of constant stimuli
MGD	Meibomian gland dysfunction
MOA	Method of adjustment
MOL	Method of limits
NaFl	Sodium fluorescein
NFV	Negative fusional vergence
NIBUT	Non-invasive tear breakup time
NIKBUT	Non-invasive keratograph breakup time
nm	Nanometres
NPC	Near point of convergence

NRA	Negative relative accommodation
NSAIDS	Non-steroidal anti-inflammatory drugs
Ofcom	The Office of Communications
OLED	Organic Light-Emitting Diode
ONS	The Office for National Statistics
OSD	Ocular surface disease
OSDI	Ocular Surface Disease Index questionnaire
P	Parvocellular
PALs	Progressive addition lenses
PDP	Plasma display panel
PEG	Polyethylene glycol
PF	Preservative-free
PFV	Positive fusional vergence
PRA	Positive relative accommodation
PSI	Pound-force per square inch
PWM	Pulse-width modulation
QD	Quantum dot
r	Pearson's correlation coefficient
RAM	Random-access memory
RCA	Radio Corporation of America
SANDE	Symptom Assessment in Dry Eye
sEBR	Spontaneous eye blink rate
SEM	Standard Error of the Mean
SM	Staircase method
TBUT	Tear film breakup time
TFOS	Tear Film & Ocular Surface Society
TFT	Thin film transistor
TMH	Tear meniscus height
UHD	Ultra-high definition
µm	Micrometre
USD	United States Dollar
UV	Ultraviolet (light)
VDT	Visual display terminal
VDU	Visual display unit
VF	Visual fatigue

VFS	Visual Fatigue Scale
VR	Virtual reality
WHO	World Health Organisation
WRRT	Wilkins rate of reading test

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Chapter 1. Display technology and digital eye strain

1.1 General introduction

Digital technologies touch almost every aspect of modern-day life and have transformed global society. Whilst communication, connectivity, and access to information has been made easier and faster, the year-on-year increase of time spent on digital devices has raised concerns about data security, privacy, and the effect on users mental and physical health. Digital eye strain, also known as computer vision syndrome, is defined as “the development or exacerbation of recurrent ocular symptoms and / or signs related specifically to digital device screen viewing” (Wolffsohn et al., 2023). In this chapter, display technology and the ownership of digital devices will be discussed, as well as the ocular and non-ocular risk factors for digital eye strain, and the other health risks associated with digital device usage.

1.1.1 Definition of key terms

Throughout the thesis, several key terms are used; these are defined below in alphabetical order.

Cognitive load - The amount of information our working memory can process at any given time (Sweller, 1988).
Computer vision syndrome - The combination of eye and vision problems associated with the use of computers (Rosenfield, 2011).
Convergence insufficiency - A binocular vision disorder where an individual is unable to fully move their eyes inwards when looking at a near target resulting in blurred vision, eye strain, headaches and diplopia (Goering et al., 2021).
Critical flicker-fusion frequency - The lowest frequency at which a flickering light is perceived as continuous (Eisen-Enosh et al., 2017).
Digital eye strain - The development or exacerbation of recurrent ocular symptoms and / or signs related specifically to digital device screen viewing (Wolffsohn et al., 2023).
Display screen - A hardware device that shows a rendered electronic image made up of pixels that are illuminated in a way that distinguishes text and graphic elements.
Dry eye - A multifactorial disease of the ocular surface characterised by a loss of homeostasis of the tear film, and accompanied by ocular symptoms, in which tear film instability and hyperosmolarity, ocular surface inflammation and damage, and neurosensory abnormalities play etiological roles (TFOS, 2017).
Privacy screen filter - A physical filter that can be attached onto a display screen designed to prevent visual hacking by limiting the viewing angle of the screen.

Screen time - The amount of time spent viewing or using digital devices with a display screen.

Visual hacking - The physical act of viewing and capturing sensitive, confidential, and private information for unauthorised use (Barker, 2019).

1.2 Display technology

Display technology is used around the world to electronically communicate information in visual form. Over the years, different display technologies have been developed. In this section, cathode-ray tubes, plasma displays, liquid crystal displays, organic light-emitting diode displays, and electronic-paper will be discussed.

1.2.1 Cathode-ray tube displays

In 1897, the German physicist Karl Ferdinand Braun invented the cathode-ray tube (CRT). A CRT converts an electrical signal into a visual display. The tube contains an electron-gun structure, which provides a narrow beam of electrons, and a phosphor screen (Figure 1.1). The electron beam is directed towards the phosphor screen and strikes it. The light emitted in a small spot is proportional to the intensity of the electron beam. By systematically and repetitively moving the spot over the entire screen, the complete image can be reproduced (Chodorow et al., 2002).

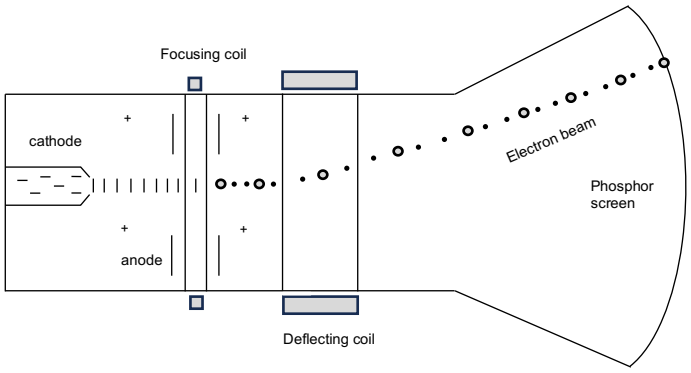


Figure 1.1. A schematic representation of a cathode-ray tube in cross-section.

The world's first practical CRT television was developed in 1926 by Kenjiro Takayanagi. From the mid-1930s onwards, CRT televisions were produced on a larger scale. Over time, CRTs changed in shape and televisions increased in size and power. Contrast, screen luminance, and resolution also improved. By 1954, Radio Corporation of America (RCA) produced the first colour-television for consumers (Herold, 1976). Up until the late twentieth

century, CRTs were used extensively in televisions, computer monitors, and radar instillations (Herres, 2019).

Several issues were experienced with CRT displays; these included veiling glare and reflections (Badano and Flynn, 1998, Roehrig et al., 2002, Haak et al., 2002), limitations to resolution (Wisnieff and Ritsko, 2000), and the perception of flicker due to the relatively low refresh rate (50-60 Hz; Bauer et al., 1983). CRT displays are also very bulky, heavy, consume a large amount of power, and are hazardous to repair due to the presence of lead and other potentially toxic materials (United States Environmental Protection Agency, 2021). Except for a few educational models and replacements for radar installations, CRT displays are no longer used.

Early publications surrounding the topic of digital eye strain (DES) / computer vision syndrome (CVS) were based on CRT technology (Nyman et al., 1985, Mikealian, 1988, Iwasaki et al., 1989, Yeow and Taylor, 1989, Dillon, 1992, Watten et al., 1994, Saito et al., 1994). With continuing technological advances and the move away from CRT displays, along with significant changes in usage patterns (section 1.2.2), early studies of DES / CVS may be less relevant today.

1.2.2 Plasma display panels

The first prototype for a plasma display panel (PDP) was invented in July 1964 at the University of Illinois, USA (Bellis, 2019). In 1992, Fujitsu introduced the world's first 21-inch full-colour plasma display (Santo, 2019). A PDP is made of two pieces of polarised glass that contain a mixture of xenon and neon gas called plasma. When a voltage is applied, plasma gas atoms become excited and ultraviolet (UV) light is released. The UV light passes through phosphor cells; each pixel contains red, green, and blue phosphor cells. By varying the current flowing through the different cells, the intensity of each colour can be increased or decreased, creating many different combinations of red, green, and blue resulting in most of the visible colours (Demers and Di Giovanni., 2021).

Several issues were experienced with PDPs; these included the high cost of manufacture, screen glare, limited brightness, and screen burn-in (image retention) - this was a common issue caused by damaged pixels whose phosphors glowed less intensely than those of surrounding pixels (May, 2021). The production of plasma displays stopped in 2014 for the United States retail market and in 2016 for the Chinese retail market due to losing nearly all

market share to low-cost liquid crystal displays and more expensive organic light-emitting diode displays (Goldman and O'Toole., 2014).

1.2.3 Liquid crystal displays

In the 1960s, the first liquid crystal display (LCD) was built at RCA Laboratories in Princeton, New Jersey, USA. The first colour flat-screen televisions hit the market in 1988 when Sharp Corporation launched its 14-inch LCD television (Kawamoto, 2012). By the late 2000s, global LCD sales had overtaken CRTs and PDPs (Sherwood, 2008).

LCDs are one of the most widely used display technologies and are commonly found in a range of devices such as smartphones, tablets, computer monitors, virtual reality headsets, televisions, and data projectors (Chen et al., 2018, Rohr and Wagner, 2020). In comparison to CRTs, LCDs offer the advantage of being much thinner, more portable, more energy efficient, and more environmentally friendly (Kyrnin, 2020). In 2020, the global TFT-LCD display market was valued around 164 billion USD and this is projected to grow to around 223 billion USD by 2026 (Business Wire., 2021).

An LCD is made of two pieces of polarised glass that contain a liquid crystal material between them (Figure 1.2). Without any voltage applied between transparent electrodes, the liquid crystal molecules are aligned in parallel with the glass surface. When a voltage is applied, the liquid crystal molecules change their orientation. Depending on their orientation, their optical characteristics vary (Schadt, 1997). An LCD consists of many pixels. Each pixel consists of three sub-pixels (red, green, and blue). To activate these sub-pixels a thin film transistor (TFT), which is a type of semiconductor device, is required in each sub-pixel. A TFT-LCD is referred to as an active-matrix display because the TFTs are arranged in a matrix on the glass of the display. To address a particular pixel, the proper row is switched on, and then a charge is sent down the correct column (Tyson, 2000).

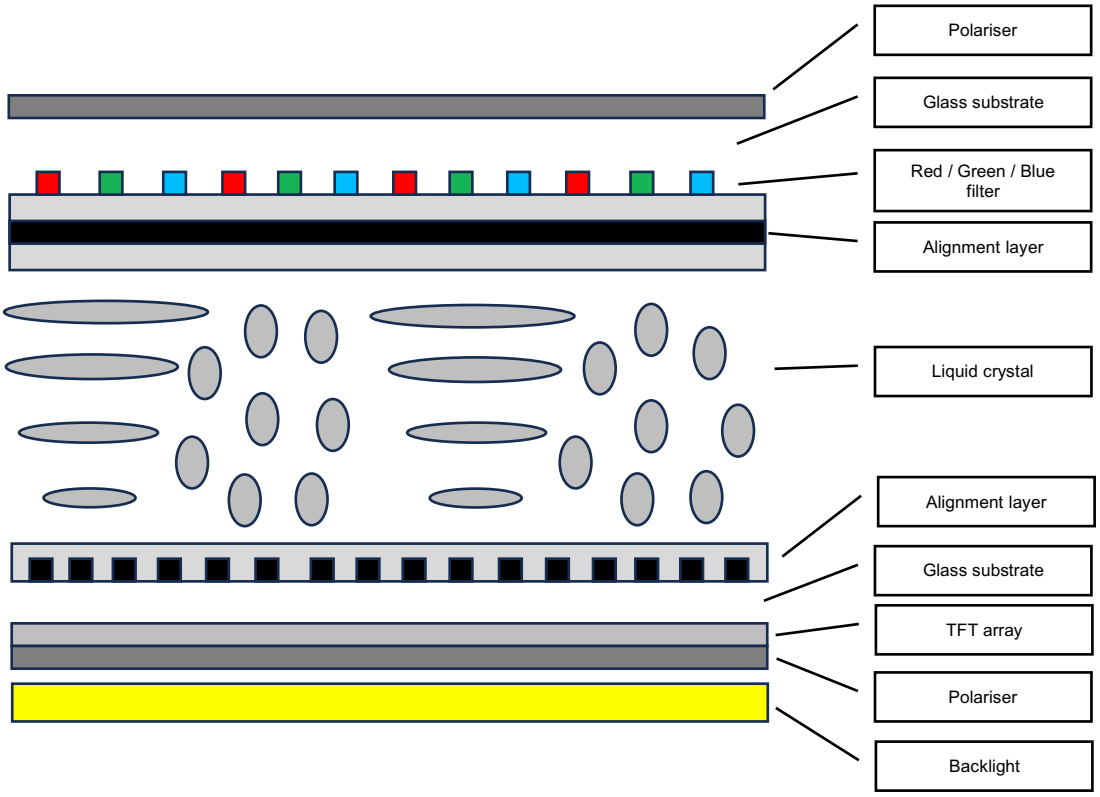


Figure 1.2. A schematic representation of a thin film transistor liquid crystal display.

1.2.3.1 Types of backlighting for liquid crystal displays

Unlike CRTs and PDPs, LCDs are not self-illuminating therefore the pixels within an LCD device require illumination from a separate component known as a backlight (Nelson- Miller, 2019). As the quality of LCDs depends on the quality of backlight used, different types of backlights have been used over the years.

1.2.3.1.1 Cold-cathode fluorescent lamps

Traditional LCDs used cold-cathode fluorescent lamps (CCFLs) as their backlight. CCFLs are sealed glass tubes filled with inert gases such as neon-argon or neon-argon-mercury (Uetsuki et al., 2009). When a high voltage is placed across the tube, the gases ionise creating UV light. The UV light then excites an inner coating of phosphor, creating visible light (Williams and McDonnell, 2012). CCFLs are not very energy efficient; at cold temperatures the lamp brightness drops significantly, and the voltage required to turn on the lamps rises significantly. CCFLs also pose a hazard due to the mercury contained within them. Around 2012, CCFL-LCD displays were discontinued by all manufacturers and replaced with light-emitting diodes (Morrison, 2013).

1.2.3.1.2 Light-emitting diodes

The first light-emitting diode (LED) that emitted visible red light was invented in 1962 by Nick Holonyak in New York, USA (LED Lighting Info, 2020). LEDs have a wide range of applications; they are used in bulbs, panel lighting, and in message displays such as microwaves and ovens, DVD players, and digital clocks (Subbaroybhat, 2020). Modern LCD backlighting involves LEDs. As LEDs are typically monochromatic, white LEDs (380-700 nm) are used (Harbers and Hoelen, 2001). During the process of electroluminescence, electrical energy is converted into non-thermal emitted light so when an electrical current is applied to white LEDs, white light is emitted; the white light is then filtered through red, blue, and green LCD sub-pixels to produce a wide range of colours and form the device's image (Braun and Heeger, 1992). For display purposes, LCDs and LEDs are the same. Frequently, televisions and smartphones are marketed as having 'LED screens', but in reality, the LED aspect only refers to the lighting source, not the display itself which is an LCD (Liang, 2021).

There are two methods of LED backlighting- full-array backlighting and edge lighting. In full-array backlighting, the LEDs are placed evenly across the entire screen in zones. Each zone can be dimmed, which is known as local dimming; this allows the display monitor to create more accurate illumination, resulting in greater picture quality. In edge lighting, LEDs are placed along the edge of the screen rather than behind it; there are no local dimming capabilities and image quality suffers. Due to the superior image quality, full-array displays are more expensive to manufacture and are typically found in more expensive equipment, whereas edge lit displays are thinner, cheaper to produce, and are more common to purchase (Cabading, 2020).

1.2.3.1.3 Quantum dots

A quantum dot (QD) is a semiconductor nanocrystal particle measuring between 1.5-10 nm (Maxwell et al., 2020). QDs exhibit both electroluminescence and photoluminescence (light emission following the absorption of photons). QDs have unique optical properties including high brightness, a long fluorescence lifetime, resistance to photobleaching and tuneable wavelengths (Brkić, 2016). One of the first applications of QDs was in QD-LCD displays, where QDs are used as phosphors to enhance the LED-LCD backlight's colour properties and efficiency. Instead of using white light LEDs, blue light LEDs are used; the QDs absorb the blue light and produce red and green light, enhancing the LED-LCD displays (Zhao et al., 2022).

1.2.4 Organic light-emitting diode displays

The first organic light-emitting diode (OLED) was developed in 1987 by Ching Wan Tang and Steven Van Slyke. In 2008, the first television featuring an OLED display entered the market (National Inventors Hall of Fame, 2021). OLEDs possess many attractive features such as high efficiency, low power consumption, wide viewing angles, and flexibility (Sudheendran Swayamprabha et al., 2021).

OLED displays are currently used in high end smartphones, tablets, virtual reality headsets and televisions (Puri, 2018). OLEDs are a solid-state semiconductor device which emit light through electroluminescence. OLED panels are made from organic (carbon based) materials and each pixel provides its own illumination, so a separate backlight is not required. The organic layers of OLEDs are much thinner than the crystalline layers in LCDs which enables OLEDs to be multi- layered and produce a much brighter image (Freudenrich, 2005). At the time of writing, OLED displays are emerging to replace LCDs in multiple consumer devices. The global OLED market size was valued around 38.4 billion USD in 2021 and this is projected to almost double to approximately 72.8 billion USD by 2026 (MarketsandMarkets, 2021).

1.2.4.1.1 Active-matrix organic light-emitting diodes

An active-matrix organic light-emitting diode (AMOLED) display is a modified version of an OLED display. The main difference between AMOLED and OLED is that an AMOLED display contains thin strips of TFTs behind each pixel which allows each pixel to be activated faster, leading to a faster refresh rate (Cabading, 2019). In 2006, the BenQ-Siemens S88 was the world’s first mobile phone to have an AMOLED display (Mertens, 2006). However, AMOLED displays have some drawbacks including lower energy-efficiency, being more prone to screen burn-in, and are costly to the consumer (Wolffsohn et al., 2023).

1.2.4.1.2 Quantum dot organic light-emitting diodes

In quantum dot organic light-emitting diode displays (QD-OLEDs), blue OLED material is used to illuminate pixels that contain red and green quantum dots. Each OLED pixel is divided into three subpixels: a blue subpixel consisting of the original blue OLED material, a red subpixel with red-tuned quantum dots, and a green subpixel with green-tuned quantum dots. The subpixels are then combined to create white light. Unlike using coloured filters, the

colour transformations performed by the QDs lose virtually no light energy making QD-OLED displays appear brighter than OLED displays whilst still maintaining the ability to be fully dimmed (Stone, 2022). At the time of writing, QD-OLED displays are somewhat of a rarity and are expensive to consumers.

1.2.5 Characteristics of LED-LCD and OLED displays

1.2.5.1 Resolution, display size and shape

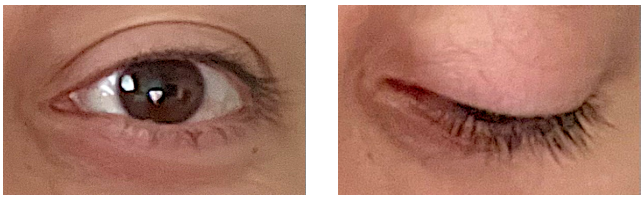
Resolution refers to the number of pixels in a digital image or display. It is defined as width (W) by height (H), (W x H), where W is the number of horizontal pixels and H is the number of vertical pixels (Tyson, 2000). Over the years, there has been a consistent trend for increasing display size in computer monitors, televisions, and mobile phones (Clark et al., 2018). As display size has increased, so too has resolution (Wolffsohn et al., 2023).

In the late 2000s, full high-definition (FHD) televisions and computer monitors became commercially available. FHD has a resolution of 1920 x 1080 which is commonly referred to as ‘1080p’ (Corning, 2020). Through advances in technology, ultra-high definition (UHD) televisions and computer monitors were manufactured; UHD has a resolution of 3840 x 2160; this resolution is known as ‘4K’. 4K monitors are currently the most popular resolution of choice for all major television brands (Pino, 2021). At the time of writing, there are a handful of displays with 8K resolution (7680 x 4320) but these are very costly to the consumer (Andrews, 2023).

LED-LCD displays are available in a variety of resolutions whereas OLED displays have 4K as their standard resolution (Killham, 2020). Both, LED-LCDs and OLEDs, display information well at the resolution they are designed for, which is known as the native resolution. However, changing the resolution scales the image, which in turn affects the image quality. Poor image quality leads to an increase in visual demand and symptoms of visual fatigue (Loh and Redd, 2008).

When viewing larger displays such as televisions and desktop computers, the eyes are usually in, or just slightly below, the primary gaze position; this viewing angle exposes a greater ocular surface area which can thin the lipid layer, alter the mucin layer, and reduce tear film stability resulting in an increased rate of tear film evaporation (Rosenfield, 2011).

When viewing smaller displays such as laptops, tablets, smartphones, or reading hardcopy text, the eyes are usually in the downward gaze position; this reduces the exposed ocular surface area, and/or the need for blinking (Wolffsohn et al., 2023). Over the years, several studies have investigated the ideal downward gaze angle to mitigate ocular dryness when viewing a digital display; slight differences in recommended angles exist but the general consensus is the optimal viewing angle should be 10-20° below the primary gaze position (Nathan et al., 1985, Tsubota and Nakamori, 1995, Pansell et al., 2007, Nielsen et al., 2008, Mehra and Galor, 2020, Kaur et al., 2022, Pavel et al., 2023).



a. Primary position of gaze b. Downward position of gaze

Figure 1.3. Photograph showing the difference in the exposed ocular surface area between the (a) primary and (b) downward positions of gaze.

In 2014, Samsung launched the world's first curved display (Business Wire., 2014). Several studies have shown that when using a curved display compared to a flat-screen display, less visual fatigue is experienced and the visual search accuracy and visual search speed of participants increases (Lee and Kim, 2016, Luo et al., 2016, Kyung and Park, 2020). In 2022, the global curved display devices market was valued around 5.79 billion USD and it is projected to grow to around 18.86 billion USD by 2030 (Vantage Market Research & Consultancy Services., 2023).

1.2.5.2 Brightness, luminance, and contrast ratio

Brightness is the perceived intensity of light coming from a visual display terminal (VDT). It is a subjective attribute of light and cannot be objectively measured. LED-LCDs are brighter than OLEDs because their backlights can be made from large and powerful LEDs (Bizzaco, 2021). Luminance describes the intensity of emitted light and can be objectively measured. It is given in candelas per square meter (cd/m^2) or nits (Tyson, 2000). The luminance of the sun is about 1.6×10^9 cd/m^2 whereas luminance ratings for digital displays typically range from 80 to 2000 cd/m^2 (Smith, 2020) which is significantly dimmer than many day-time real-world situations (Wolffsohn et al., 2023).

High screen luminance has been shown to improve image quality, however, working under high screen luminance (140 cd/m^2) for a prolonged period of time (one hour) has been shown to decrease the number of eye blinks performed and increase visual fatigue (Benedetto et al., 2014). Adjusting screen brightness in accordance with the ambient light has been shown to reduce the prevalence of DES (Ranasinghe et al., 2016a, Zayed et al., 2021) but not influence the severity of symptoms (Ranasinghe et al., 2016a).
Dark mode is a display setting which darkens the user interface. Light-coloured text (white or grey) is presented against a dark or black screen with the aim of reducing eye strain in low ambient light conditions and minimising the display's influence on the circadian rhythm (Erickson et al., 2020, Schreiner, 2020). Currently, there is limited evidence on how dark mode impacts ocular health, ocular comfort, and vision (Wolffsohn et al., 2023). Further research is required to better understand the optimum display mode for specific devices over a range of lighting conditions, so that text legibility can be maximised, and visual fatigue minimised (Wolffsohn et al., 2023).

Contrast ratio is the ratio between the maximum and minimum luminance, or in other words, the ratio between the brightest white and darkest black that a monitor can reproduce (Tyson, 2000). The average contrast ratio of LED-LCD monitors is 1000:1, but some can be as much as 3000:1 (Smith, 2021). Contrast on an OLED display is far greater because when an OLED screen goes black, its pixels produce no light. In theory, this means OLEDs have an infinite contrast ratio, although this does depend on how bright the OLEDs can go when they are illuminated (Monney, 2021). Over the years, several studies (Zhu and Wu, 1990, Saito et al., 1993, Shieh and Lin, 2000, Wang and Chen, 2000) have researched the effects of contrast ratio and text colour on visual performance when using a VDT. However, older CRT and TFT-LCD displays were used so the results of these studies may not apply to more modern displays such as LED-LCDs or OLEDs. Contrast sensitivity tends to be reduced in dry eye sufferers (Koh et al., 2017, Szczotka-Flynn et al., 2019) but currently there are no known studies exploring the association between DES symptoms and contrast sensitivity.

1.2.5.3 Illumination and glare

Illumination is a measure of the light falling upon a surface and comes from a variety of sources such as windows and lights (National Research Council US, 1983). Various studies (Lin, 2014, Chen et al., 2016, Liu et al., 2017b, Huang et al., 2017, Boyce and Carter, 2018, Hamedani et al., 2019, Zhou et al., 2021) have investigated the relationship between ambient illumination, visual comfort and visual fatigue when using a VDT but the findings have been varied with no general consensus found.

Glare can be categorised into three types: disability glare, discomfort glare and reflected glare. Disability glare describes the loss of retinal image contrast due to intraocular light (straylight) scatter. Straylight casts a veiling luminance on the retina, reducing image contrast and impairing vision (Aslam et al., 2007).

Discomfort glare is defined as a subjective feeling of annoyance or pain induced by an overly bright light source in the field-of-view, without necessarily impairing the visibility of objects (Wolffsohn et al., 2023). Discomfort glare has been objectively evaluated by recording the electromyographic responses of the ocular muscles (Murray et al., 2002) and by using an eye-tracker and electroencephalography (Akimoto and Miyake, 2023).

A reflection is when light bounces off an object; reflected images can produce a veil of light, known as reflected glare, over a portion of the display screen. Reflected glare can be caused by sunlight, overhead lights, and task lamps. Since reflected images form at distances other than that of the screen surface, ocular accommodation and convergence tend to fluctuate; this can negatively impact the user's binocular vision system leading to symptoms of visual fatigue and reduced task performance (Shieh, 2000).

1.2.5.4 Refresh rate

The refresh rate of a display, measured in Hertz (Hz), refers to how many times per second the display can generate a new image. Low refresh rates risk a flickering or jerky image whereas high refresh rates produce smoother images (Wolffsohn et al., 2023). Table 1.1 shows the different types of visual displays and their typical refresh rate.

Older studies using CRT monitors showed that their low refresh rate (50-120 Hz; Bauer et al., 1983, Menozzi et al., 2001) may negatively affect accommodation, blink rate, and reading speed (Jaschinski et al., 1996) but not saccadic eye movements (Jainta et al., 2004). A 2009 study measured the degree of eye strain caused by watching LCD and PDP displays by analysing eye blinking and changes in pupil sizes. The study found that the degree of eyestrain was greater when watching LCD displays compared to when watching PDP displays (Lee et al., 2009). TFT-LCDs and OLEDs have higher refresh rates (60-240 Hz; Kim et al., 2019, Khullar, 2023) but their effects on certain parameters including accommodation, pupil size, and the critical flicker-fusion frequency appear to remain unknown due to an apparent scarcity of modern-day research.

Type of visual display	Typical refresh rate
Cathode-ray tube displays	50-120 Hz (Bauer et al., 1983, Menozzi et al., 2001)
Plasma display panels	48-70 Hz (Silva, 2022)
Liquid crystal displays	60-240 Hz (Kim et al., 2019)
Organic light-emitting diode displays	60-240Hz (Khullar, 2023)

Table 1.1. Table showing different types of visual display and their typical refresh rate.

The critical flicker-fusion frequency (CFF) is the lowest frequency at which a flickering light is perceived as continuous. Phone manufacturers dim displays through a technique called pulse-width modulation (PWM); this is where diodes are turned on and off at varying rates. The PWM of OLED displays range around 50 to 500 Hz, whereas the PWM of LCD displays start around 1000 Hz or higher (Anderson, 2021). For many years it was believed that the human eye could only detect flicker up to 90 Hz, however, Davis *et al*. (2015) found that humans can perceive visual flicker artifacts at rates over 500 Hz (Davis et al., 2015). Due to the inherent flicker associated with the PWM technique (Wang et al., 2014), the study performed by Davis *et al*. (2015) may substantiate claims that users of OLED displays are more likely to experience eye strain and headaches (Anderson, 2021, Yuan et al., 2021).

1.2.6 Head-mounted devices

Virtual reality (VR) head-mounted displays have been around since the 1960s (Virtual Reality Society., 2019) but their popularity has soared in recent years with an estimated 171 million global users at the end of 2023 (Jayaraman, 2024). A VR head-mounted device can either be connected to a computer or can be an all-in-one device which completely covers the eyes and comprises of a stereoscopic digital display with associated optics, stereo sound, head-mounted tracking sensors and handheld controllers generating an immersive experience in the virtual environment (Wolffsohn et al., 2023). Numerous adverse health-related issues have been associated with the use of VR head-mounted devices including virtual motion sickness, binocular vision issues, neck / back strain and the increased risk of falling (Wolffsohn et al., 2023).

Augmented reality headsets are head-mounted devices that overlay computer generated virtual objects onto the wearer's real-world view (Chen et al., 2019). The first augmented reality headsets were developed in the late 1960s to aid United States Airforce pilots (Van

Krevelen, 2007). A wide range of optical technologies have been utilised when developing augmented reality headsets including holographic, diffractive and reflective waveguides. Due to their high cost and safety concerns (reality modifications and privacy concerns), augmented reality headsets are generally reserved for enterprise solutions (Wolffsohn et al., 2023).

1.2.7 Electronic paper

Electronic paper, also known as e-paper, electronic ink, or E Ink, is a type of reflective display technology that mimics the appearance of ordinary ink on paper. Electronic paper does not require a backlight and is described as an electrophoretic display (EPD) because it functions based on the motion of dispersed particles in a fluid under the influence of an electric field (Primozic, 2015). EPDs are made up of millions of tiny microcapsules, with a diameter in the size of a human hair (~40 μm). Each microcapsule contains oppositely charged black and white pigments suspended in a clear fluid. The capsules are fixed to a substrate and sandwiched between electrodes. When an electric field is applied, one pigment is drawn to the positive electrode, and one to the negative electrode, see figure 1.4 (DeJean, 2008, Siegenthaler et al., 2012b).

The basis of e-readers is e-paper. In 1998, the first commercial e-reader named the ‘Rocket eBook’ was launched (Kozlowski, 2018). Due to very little consumer interest, it was quickly discontinued. The next e-readers were released in the early 2000s (Day, 2021). In recent years, the popularity of e-readers has grown. Estimates show that 191 million e-books were sold in the United States in 2020 (Statista, 2020) and 72 million were sold in the United Kingdom in 2021 (Erudera, 2023).

E-readers have very low power consumption and are high contrast displays with low amounts of glare (Wolffsohn et al., 2023). Reading time, reading behaviour (legibility), engagement, blink dynamics, eye movements, and pupil size are generally comparable between e-paper and printed paper (Siegenthaler et al., 2011, Wu, 2011, Siegenthaler et al., 2012a, Benedetto et al., 2013). E-readers are generally viewed in the downward gaze position which may play a role in reducing corneal exposure (Talens-Estarelles et al., 2020). DES is typically less apparent with e-paper (Siegenthaler et al., 2012a, Benedetto et al., 2013, Talens-Estarelles et al., 2020) although this is not always the case (Prabhasawat et al., 2019).

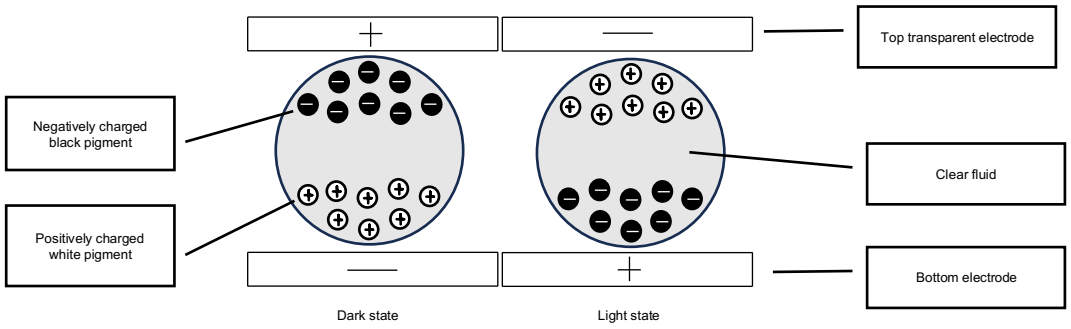


Figure 1.4. A schematic representation of an electrophoretic display when an electric charge is applied.

Multiple studies comparing screens and paper-based tasks have concluded that people comprehend more, read faster, and read more accurately on paper (Muter et al., 1982, Wilkinson and Robinshaw, 1987, Dillon, 1992). Jeong *et al*. (2021) found that reading comprehension and reading time were equivalent when participants read on printed text, a computer, and a tablet. However, when reading on printed text, higher levels of perceived understanding, confidence, and immersion and lower levels of perceived fatigue were reported. Despite the narrowing performance gap between printed text and screen, the findings of this study show that printed text may still be the preferred mode of reading (Jeong and Gweon, 2021).

A consideration of the characteristics of display technology such as flicker, high contrast, and fluctuating luminescence highlights some of the differences between the two mediums. E-readers are associated with ocular comfort as they reflect ambient light like a paper book, whereas reading on self-illuminated screens tends to cause eyestrain, headaches, and blurred vision (Benedetto et al., 2013). It has been suggested that lower performance using a screen might be attributable to an increase in cognitive demand (Noyes and Garland, 2008, Jabr, 2013). In the thesis, visuo-ocular symptoms during prolonged (one-hour) digital tasks will be tracked and the impact of higher and lower cognitive load levels on visuo-ocular symptoms, productivity, and task accuracy will be examined (Chapter 6).

1.3 The History, ownership, and usage trends of digital devices

1.3.1 Brief history of computers and smartphones

The first commercial computer, the Remington Rand Univac, was produced in 1951 and weighed over 7000 kilograms (kg). The main memory was around 1.5 kilobytes (kB) and

consisted of tanks of liquid mercury (Computer History Museum., 2022). In 1975, the MITS Altair 8800, was one of the first personal computers to become commercially available and it sold for around $3000 USD in today's prices (Knight, 2014). It had a random-access memory (RAM) of 256 bytes but this could be expanded to 64 kB and the user added a CRT monitor separately (Iandiorio, 2014).

In 1981, the Osborne 1, was the first portable computer that included a 5-inch monochrome CRT monitor with a resolution of 52 characters in 24 rows, disk drives, and all components. It had 65 kB of RAM and weighed around 11 kg (MLN, 2021). The world's first thinnest laptop, the MacBook Air, was produced in 2008 (Tinari, 2016). It had an LED-LCD display measuring 13.3 inches with a native resolution of 1280 x 800, 2 gigabytes (GB) of RAM and weighed 1.36 kg (Ackerman, 2018). In comparison, the MacBook Air released in 2023 has a 15.3 inch LED-LCD display with in-plane switching (IPS) technology; this technology was first introduced by Hitachi in 1996 and was developed to correct the poor viewing angles and colour problems that LCD displays had at the time (Brandrick, 2010), a native resolution of 2880 x 1864, up to 24 GB of RAM and weight of 1.51 kg (Apple, 2023b).

The first handheld cellular telephone, the Motorola DynaTAC 8000X, was produced in 1984. It had an LED display, was 9 inches tall, weighed just over 1 kg and had around 35 minutes of talk time. It sold for around $10,000 USD in today's prices (Science Museum, 2018). In 1992, the IBM Simon was the first touchscreen phone and weighed around 510 grams (g). It had an LCD display, around 60 minutes of talk time, and was able to send and receive faxes, emails, and cellular pages (Jackson, 2018). When Apple launched the iPhone in 2007, the smartphone revolution was born. The iPhone was the first multipurpose handheld computing device combining mobile telephone, music player, digital camera, and personal computing technologies (Encyclopaedia Britannica., 2020). It weighed 136 g, had a 3.5-inch touchscreen LCD display with a native resolution of 320 x 480 and up to 8 hours talk time (HISTORY.com., 2020). In comparison, the iPhone 16 released in 2024 has up to 80 hours audio playback, is 5.81 inches tall, weighs 170 g, and has a 6.1-inch touchscreen OLED display with a 2556 x 1179 native resolution (Apple, 2023a). It should be noted that other manufacturers also produce high-quality smartphones such as Samsung's Galaxy S24 Ultra (also released in 2024) which has up to 95 hours audio playback, 6.2-inch touchscreen AMOLED display with a 3120 x 1440 native resolution (Samsung, 2024).

Computer and smartphone technology has greatly advanced over the past seventy years and thirty years respectively. Computers and smartphones have generally become smaller, lighter, have far superior technical specifications, and have become much more accessible.

In the following section, the trends in ownership of digital devices and internet access / usage in the UK and USA will be discussed; the USA has been selected as it is one of the most technologically advanced countries in the world (Global finance., 2022) and has robust digital device and internet usage data from the 1980s onwards.

1.3.2 Trends in ownership and usage of digital devices and the internet

1.3.2.1 The United Kingdom

Robust data from the UK is only available from 2006 onwards. A 2018 report by 'The Office of Communications' (Ofcom) showed that in 2008, 17 % of the UK population owned a smartphone, by 2018 this percentage had risen to 78 % and by 2023 it had risen further to 94 % (Ofcom, 2018, Statista, 2023b). As of January 2023, 96 % of UK households had access to the internet, up from 57 % in 2006 when comparable records began (Office for National Statistics, 2020, Clark, 2023).

The World Health Organisation (WHO) released guidelines in 2019 on physical activity, sedentary behaviour, and sleep for children aged under 5 years old. The guidelines recommended that children under two years should not have any screen time, whilst children aged between 2-5 years should have no more than one hour a day of sedentary screen time (World Health Organisation., 2019). The year before these recommendations were released, data collected by Ofcom found that 52 % of children aged between 3-4 years went online for nearly 9 hours per week, and 99 % of children aged between 12-15 years went online for 20.5 hours per week (Ofcom, 2018). It is unclear how Ofcom measured these time durations. If the information was obtained from parents, it is likely that the true figures could be very different / higher than what is stated in the report. Both sets of age groups had access to multiple digital devices. In the 3-4 years age group, 1 % had their own smartphone and 19 % had their own tablet. In the 12-15 years age group, 83 % had their own smartphone and 50 % had their own tablet (Ofcom, 2018).

In 2013, 'The Office for National Statistics' (ONS) reported that computer usage amongst UK adults had risen from 45 % in 2006, to 70 % in 2013 (Office for National Statistics, 2013). Due to the COVID- 19 pandemic, the UK experienced its first lockdown in March 2020. As the population was ordered to stay at home, digital device usage soared, and 92 % of adults admitted to being regular internet users (Office for National Statistics, 2020). During this period, children aged 5-16 years spent on average 6.3 hours per day viewing a screen

(NHSGGC, 2021) and adults spent 6.4 hours per day (Ofcom, 2021). Since the ONS survey began, UK adults aged 75 years and over have consistently been the lowest users of the internet. In 2013, 29.1 % of this age group were internet users. The most recent report produced by the ONS in 2020 showed the number of UK adults aged 75 years and over using the internet had risen to 54 %, see figure 1.5 (Office for National Statistics., 2020).

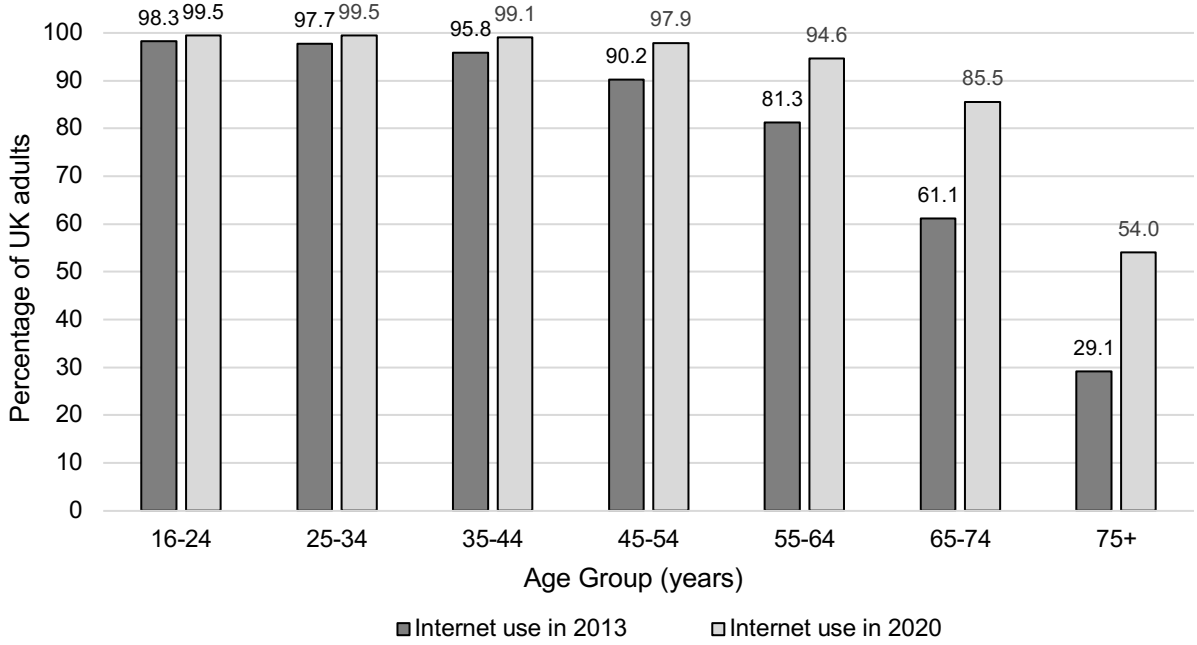


Figure 1.5. Bar chart showing the percentage of UK adults who used the internet in 2013 and 2020 respectively against the relevant age group.

1.3.2.2 The United States of America

The most recent data published by the United States Census Bureau showed that ownership of computers (desktops, laptops, tablets, and smartphones were all considered as computers) by American households steadily increased from 8.2 % in 1984 to 92 % in 2018 (Kominski, 1988, United States Census Bureau, 2021) with smartphone ownership (84 % of all households) surpassing ownership of all other computing devices (United States Census Bureau, 2021).

Within the American adult population, the age groups with the highest percentage of internet use have consistently been 18-29 years and 30-49 years, whereas the age group with the lowest percentage of computer use have consistently been 65 years or above, see figure 1.6 (Kominski, 1988, United States Census Bureau, 1993, United States Census Bureau, 2003, United States Census Bureau, 2012, United States Census Bureau, 2021).

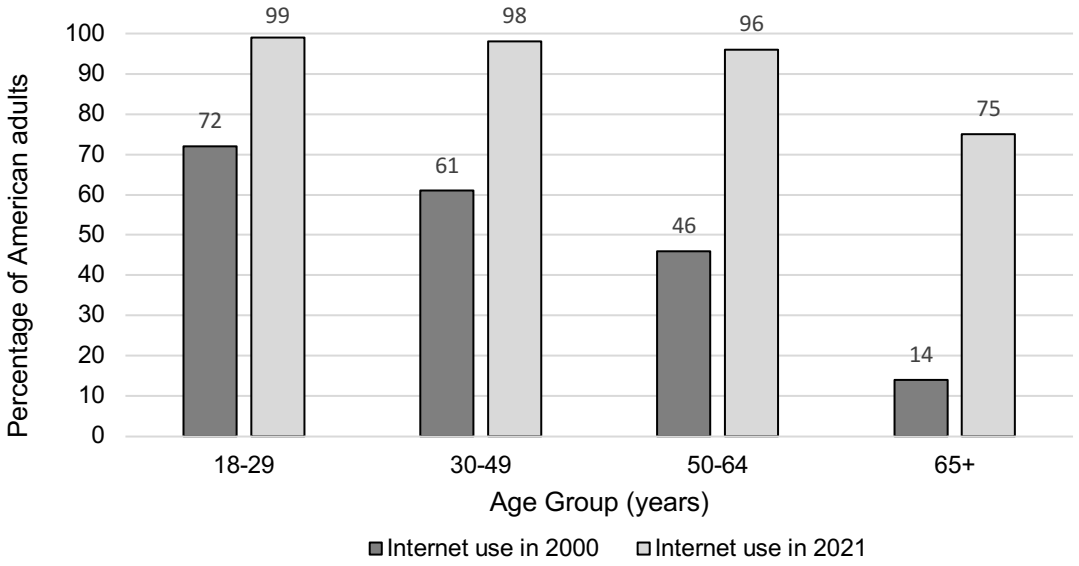


Figure 1.6. Bar chart showing the percentage of American adults who used the internet in 2000 and 2021 respectively against the relevant age group.

1.3.2.3 Asia

The Asian continent covers 30 % of the Earth's land area and has a population of just under 5 billion people (WorldPopulationReview, 2024). The 4 most populous Asian countries, India, China, Indonesia and Pakistan have all undergone a digital revolution over the past 20 years with internet users in China rising from 2 % in 2000 to 77 % in 2024, while Indonesia's internet users grew from 1 % to 69 % over the same period. The pace has been slightly slower in South Asia, with internet users in India and Pakistan reaching 52 % and 37 % by 2023 respectively (Teutem, 2025). As of 2024, 62 studies investigating DES within the Asian continent had been published and the prevalence of DES was reported to be between 60.5 to 78.6 % (Ccami-Bernal et al., 2024).

1.3.2.4 Africa

Africa is a latecomer to digitalisation and access to digital devices and the internet varies between African countries. Between 2010 and 2023, internet users across the African continent grew from 9.6 % to 37 % (ITU, 2024). In Burundi, Africa's poorest country, only 11 % of its population has access to the internet (Kemp, 2024b). In stark contrast, 79 % of South Africans (one of Africa's wealthiest countries) have access to the internet (Statista, 2024a). In 2020, the prevalence of DES during the COVID-19 lockdown was recorded as 64 % amongst a South African university student population (Munsamy et al., 2022b).

1.3.2.5 South America

Around 80 % of South Americans have access to smartphones and the internet, and this figure is expected to rise to 92 % by 2030 (Statista, 2024b). In Brazil, South America's largest country, 93 % of households use the internet compared to only 58 % in 2015 (Statista, 2023a). In a 2012 study, over 50 % of call centre workers in Sao Paulo, Brazil, who worked 36 hours per week with a break time of between 21 to 35 minutes per day, reported experiencing DES (Sá et al., 2012).

1.3.2.6 Australasia

95 % of Australians use the internet, with mobile phones being the most frequently used digital device (ACMA, 2023). Approximately 75 % of working New Zealanders use the internet daily and 99 % use it once a week (or more often) at home (ITA, 2024). The quality and availability of internet infrastructure varies widely across the other island nations, but internet speeds are typically slow due to the region's geographical remoteness.

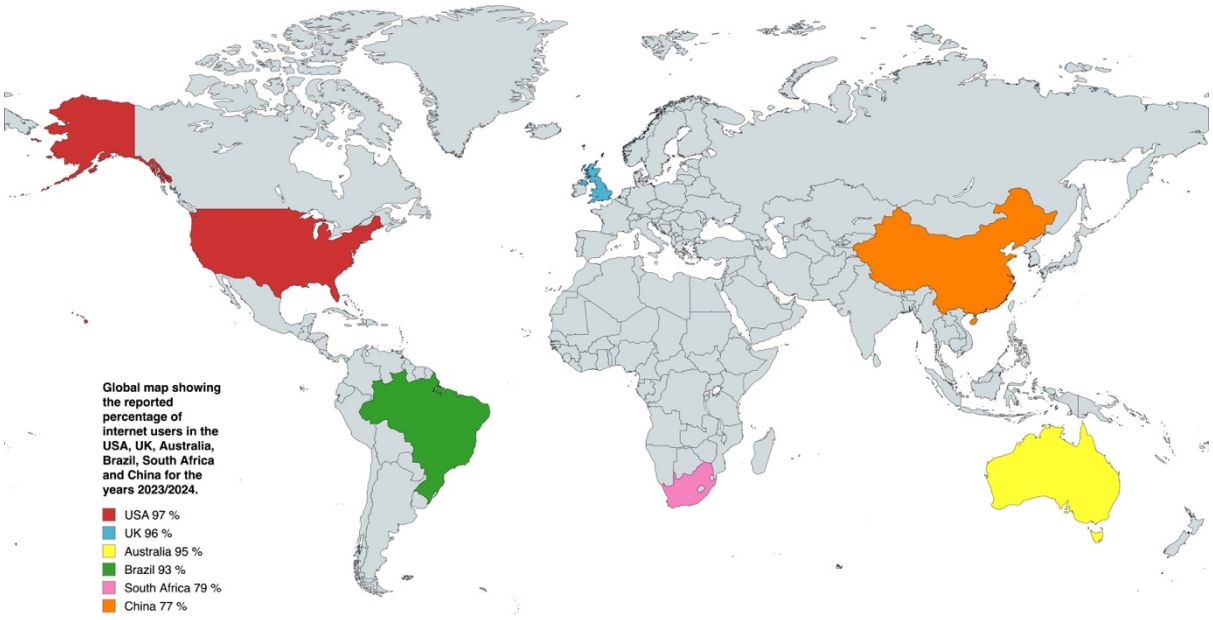


Figure 1.7. Global map showing the reported percentage of internet users in the USA (97%), UK (96%), Australia (95%), Brazil (93%), South Africa (79%) and China (77%) for the years 2023/2024.

1.3.3 Media multitasking

Some research suggests that pre-schoolers may become familiar with digital devices before they are exposed to books (Hopkins et al., 2013). A 2017 study found that American youth (8- to 18-year-olds) spent an average of 7.5 hours per day, every day, interacting with media, and on average 29 % of that time was spent media multitasking (Uncapher et al., 2017). Media multitasking is the simultaneous use of different media such as scrolling on a smartphone whilst also using a laptop, or using a digital device while doing another task, such as using a smartphone while eating (Domoff et al., 2020). Over the past decade, media multitasking has become increasingly prevalent (Beuckels et al., 2021). As media multitasking is a more recent phenomenon, the effects are not fully known but emerging research has indicated that media multitasking is associated with changes in cognitive control resulting in failures of everyday executive functioning, poor mental health, and lower academic achievement (Uhls et al., 2011, Parry and le Roux, 2019, Cardoso-Leite et al., 2021).

1.4 Digital eye strain

Digital device usage has been associated with a range of health consequences, both ocular and non-ocular. As device usage has reached saturation in most age groups, adverse health effects are becoming more prevalent. Digital eye strain (DES) is defined as “the development or exacerbation of recurrent ocular symptoms and / or signs related specifically to digital device screen viewing” (Wolffsohn et al., 2023). DES has been a recognised health problem for over 20 years and has high prevalence levels; values of up to 98 % have been reported in adults, but around 72 % is more typical (Wolffsohn et al., 2023). Symptoms of DES include blurred vision, diplopia, difficulty focussing at near, asthenopia, headache, tired and sore eyes, dryness, burning, tearing, irritation, along with musculoskeletal issues such as neck and shoulder pain and back ache.

1.4.1 Digital eye strain questionnaires

Over the years, a variety of questionnaires have been developed to identify DES sufferers and grade the severity of symptoms (Chapter 8, Table 8.1). Most DES questionnaires are custom made and list various ocular and non-ocular symptoms. These questionnaires are usually translated into the country's main spoken language by the authors, lacking validation and not accounting for cultural perceptions. Consequently, DES is diagnosed inconsistently

making it difficult to compare its prevalence across different countries (Wolffsohn et al., 2023).

The most widely used, validated DES questionnaire is the Computer Vision Syndrome Questionnaire (CVS-Q). The CVS-Q uses a single rating scale to assess the frequency and intensity of 16 symptoms (experienced in a week) where 6 points or more is considered diagnostic of the condition (Seguí Mdel et al., 2015). To calculate the severity of symptoms, the 'frequency' column score ('never' = 0; 'occasionally' = 1; 'often or always' = 2) is multiplied by the 'intensity' column score ('moderate' = 1; and 'intense' = 2), so the following severity scores can be obtained: 0 (0x1 or 1x0); 1 (1x1); 2 (1x2 or 2x1); and 4 (2x2). Following Rasch analysis, the research group responsible for designing the CVS-Q decided on three categories for the severity score: 0, 1 (1x1), and 2 (1x2, 2x1, 2x2). The severity scores for each symptom are then added together. The maximum score which can be obtained is 36. Despite it not being compared against a gold standard (Seguí Mdel et al., 2015), its suboptimal item-person targeting, its inability to assess symptoms in real time, the large overlap between dry eye symptoms and its lack of widespread clinical use, the CVS-Q appears to be the questionnaire of choice when researching DES and has been used in numerous global studies (Tauste et al., 2016, Dabrowiecki et al., 2020, Sánchez-Brau et al., 2021, Yammouni and Evans, 2021, Lin et al., 2022, Talens-Estarelles et al., 2022a). More recently, the 'CVS-Q teen' questionnaire has been released; this adapted version of the CVS-Q has been developed to assess DES symptomology in adolescents aged 12-17 years and consists of 14-items where a score ≥ 6 is considered diagnostic of the condition. However the CVS-Q teen has only been designed for the Spanish adolescent population and has not been validated in other cultural and linguistic contexts (Seguí-Crespo et al., 2024).

1.4.2 Ocular risk factors for digital eye strain

Ocular risk factors for DES can be split into 5 categories: uncorrected refractive errors, binocular vision anomalies, pupil size, blinking dynamics, and dry eye disease.

1.4.2.1 Uncorrected refractive errors

Uncorrected refractive errors can lead to blurred vision, asthenopia, diplopia, and frontal headaches (Heus et al., 2018). Correction of refractive error, particularly astigmatism and presbyopia, is an important intervention in DES sufferers (Sheppard and Wolffsohn, 2018). Correction of high myopia and spherical hyperopia (there is a paucity of published research

on correction of hyperopia in device users) is also important, as it minimises blur and reduces the ocular stimulus to accommodation (Rosenfield, 2011). The law in the UK states that employers must arrange an eye test for display screen equipment (DSE) users if they ask for one and provide glasses if an employee needs them for DSE use (The Health and Safety [Display Screen Equipment] Regulations, 1992).

1.4.2.1.1 Astigmatism

Astigmatism results from an irregular curvature of the cornea, the lens, or both. A 1991 study found that small amounts of uncorrected astigmatism (+0.50 DS x 90) can give rise to eye strain when using a VDT (Wiggins and Daum, 1991). The following year, the same researchers found that when the residual astigmatism of soft contact lens wearers was corrected, greater visual comfort when viewing a VDT was reported (Wiggins et al., 1992). Both studies found that 0.50 to 1.00 dioptres (D) of uncorrected astigmatism produced a significant increase in symptoms (Wiggins and Daum, 1991, Wiggins et al., 1992). Twenty years later, Rosenfield *et al*. (2012) reported that the change from -1.00 to -2.00 D of induced oblique astigmatism produced a significant increase in post-computer task symptoms (Rosenfield et al., 2012). These studies demonstrate that correcting even modest astigmatic refractive errors is important when trying to minimise symptoms of DES.

1.4.2.1.2 Myopia

Myopia is a condition in which the spherical equivalent objective refractive error is less than, or equal to -0.50 D in either eye and high myopia is where the refractive error is less than, or equal to -5.00 D in either eye (World Health Organisation., 2015). Although the overall risk of ocular pathologies such as cataract, glaucoma, retinal detachment, and myopic macular degeneration is greater in high myopes (Holden et al., 2016), slowing the progression of myopia during childhood, even by 1 dioptre, should reduce the likelihood of a patient developing myopic maculopathy by 40 % (Bullimore and Brennan, 2019). Currently, there is no significant relationship between screen time and myopia (Foreman et al., 2021, Xie et al., 2022) so it is unlikely that DES itself causes myopia. However, myopia progression may be driven by long periods of near-vision work and inadequate outdoor time (Logan et al., 2021), both of which are also risk factors for DES.

1.4.2.1.3 Presbyopia

Presbyopia is the age-related loss of lens accommodation resulting in an inability to focus at near. Jaschinski *et al*. (2015) found that even in the early stages of presbyopia, individuals who were missing a near-vision addition were at risk of experiencing DES when performing demanding computer work (Jaschinski et al., 2015b). Different types of spectacle lenses are used to manage presbyopia; these include single vision, bifocal, and progressive addition lenses (Wolffsohn and Davies, 2019).

1.4.2.1.4 Correction of refractive errors

Single vision lenses have just one optical prescription correction. Focus is evenly distributed over the entire lens surface which prevents any image distortion, regardless of the viewing angle. As digital devices are viewed at variable distances, multiple pairs of single vision spectacles may be required by presbyopes for adequate vision across the range of demand levels (Rosenfield, 2011, Sheppard and Wolffsohn, 2018).

The two-in-one design of bifocals provides both distance and near, or intermediate and near vision correction at a relatively low cost, however, users can experience image jump when transitioning from the different optical prescriptions. Desktop monitors are generally placed at, or just below, primary gaze therefore the positioning of a standard bifocal spectacle lens near segment may be inappropriate for this task (Rosenfield, 2011). Some studies have found that when viewing a VDT, bifocal users experience significantly more neck and back discomfort compared to when single vision lenses are used (Balci and Aghazadeh, 1998, Basrai and Aghazadeh, 2004).

Multifocal lenses / PALs (also known as varifocals) provide a continuous change in power, supplying distance, intermediate and near vision correction without the wearer having to switch between multiple pairs of spectacles. However, the design of these lenses encourages a person to hold their head in a more forward position (Willford et al., 1996), leading to greater degrees of occipital extension which increases the risk for musculoskeletal disorders and headaches (Becker et al., 2007).

Computer vision PALs / occupational lenses are specifically directed at people who spend a lot of time in a computer environment. These types of lenses have wider intermediate and near vision areas but no clear distance vision. A 2015 study involving 23 presbyopic participants found that the vision obtained at the computer monitor was significantly better

when using computer vision PALs (Jaschinski et al., 2015a). Another study involving 190 presbyopic visual display unit (VDU) workers used a 24-item questionnaire (developed specifically for this study) to assess comfort and lens type preferences and found that computer vision PALs were statistically and clinically significantly better than general purpose PALs in reducing the perception of DES (Kolbe and Degle, 2018).

Accommodative support lenses are a low add progressive addition spectacle lens designed to ease DES symptoms in pre-presbyopes. A 2020 study showed that individuals with good amplitudes of accommodation (any participant with an accommodative anomaly, measured by RAF rule, ± 1.50D flippers, and MEM retinoscopy, was excluded from the study) may prefer a low reading add of +0.75 D when using a desktop computer to help ease symptoms (symptomology was measured using the CVS-Q and Symptom Assessment in Dry Eye (SANDE) questionnaires) (Yammouni and Evans, 2020). In contrast to this, a 2022 study instructed participants to wear spectacles for all work with electronic displays over a 6-month period. The findings showed no significant improvement in the CVS-Q scores in individuals wearing accommodative support lenses (+0.75 D add) compared to those who did not wear them (control lenses were standard single vision aspheric lenses, 1.6 refractive index) (Del Mar Seguí-Crespo et al., 2022).

1.4.2.2 Binocular vision anomalies

Binocular vision anomalies are usually associated with symptoms such as headaches, asthenopia, eye pain, blurred vision, and diplopia. In this section, a brief overview of the extraocular muscles, ocular alignment, binocular single vision, stereopsis, accommodation, vergence, and their relationship with digital device usage will be discussed.

1.4.2.2.1 The extraocular muscles

There are six extraocular muscles which are responsible for the movement of the eye. These are grouped into three antagonistic pairs: the lateral and medial recti, the superior and inferior recti, and the superior and inferior obliques. The recti muscles all share a common origin, a fibrous ring of connective tissue located posteriorly at the apex of the orbit called the tendinous ring or the annulus of Zinn. The oblique muscles have bony origins within the orbital cavity (Van Aswegen, 2021). The levator palpebrae superioris (LPS) is primarily responsible for eyelid elevation. The LPS originates from the lesser wing of the sphenoid bone and is innervated by the 3rd cranial nerve (Ferng, 2021). The primary blood supply for all the extraocular muscles are the muscular branches of the ophthalmic artery, lacrimal

artery, and infraorbital artery. Venous drainage is similar to the arterial system and empties into the superior and inferior orbital veins (Shumway et al., 2021).

Innervation	Muscle	Action
3rd cranial nerve	Medial rectus	Adduction
3rd cranial nerve	Superior rectus	Elevation, adduction, and intorsion
3rd cranial nerve	Inferior rectus	Depression, adduction, and extorsion
3rd cranial nerve	Inferior oblique	Extorsion, elevation, and abduction
4th cranial nerve	Superior oblique	Intorsion, depression, and abduction
6th cranial nerve	Lateral rectus	Abduction

Table 1.2. Table showing the actions and innervations of the extraocular muscles.

1.4.2.2.2 Ocular alignment

During perfect ocular alignment, both eyes fixate simultaneously on a target. If either eye is covered, no movement will take place which is known as orthophoria. Heterophoria, which is also known as latent deviation or latent squint, is where the visual axes achieve union, but only through the effort made by the horizontal and vertical fusional reserves (Evans, 2022). The fusional reserves are an objective measure of the eyes' ability to maintain the correct balance of convergence and divergence at distance and near to overcome a heterophoria through the use of a prism bar (Sassonov et al., 2010). If the fusional reserves achieve this easily, the heterophoria is regarded as compensated. If the fusional reserves are unable to control any deviation, the heterophoria is regarded as decompensated, and this gives rise to symptoms such as blurred vision, asthenopia, diplopia, headaches, and difficulties in changing focus from distance to near and vice versa (Evans, 2022).

Heterotropia, which is also known as manifest strabismus or squint, occurs when the visual axes do not coincide at the object of interest, or at infinity for distance viewing (Dabasia, 2010). The misalignment of the visual axes may be present occasionally or constantly (Fang, 2021). Onset is usually within childhood. Unsuccessful treatment, or no treatment, may

result in amblyopia which is a unilateral or, less commonly, bilateral reduction in visual acuity that cannot be corrected with glasses or surgery (Doshi and Rodriguez, 2007). Adults can develop a strabismus but this is usually secondary to various conditions such as cranial nerve palsies, neurological diseases, thyroid dysfunction, trauma, or surgical procedures (Martinez-Thompson et al., 2014).

1.4.2.2.3 Binocular single vision

Corresponding retinal points are two points, one in each retina, which when simultaneously stimulated give rise to the perception of a single object (Piano and O'Connor, 2013); this is referred to as binocular single vision (BSV). The retinal points fall on an area called the horopter. The volume of space surrounding the horopter, over which we perceive single vision, is known as Panum's fusional space (Figure 1.8). Points lying outside this area result in physiological diplopia. Under normal viewing conditions, the visual system suppresses this diplopia and it is not experienced (Kalloniatis and Luu, 1995). Fixation disparity (FD) is a very small ocular misalignment within Panum's fusional space under BSV conditions (Karania and Evans, 2006) which leads to a fused fixation point not being projected onto the centre of the fovea in each eye (Jaschinski et al., 1999a). Decompensated heterophorias tend to have a fixation disparity.

1.4.2.2.4 Stereopsis

BSV results in stereopsis which is defined as the perception of depth that arises from the lateral displacement of the two eyes; this provides two slightly different views of the same object (disparate images) and results in the most precise kind of depth perception (Hibbard et al., 2017).

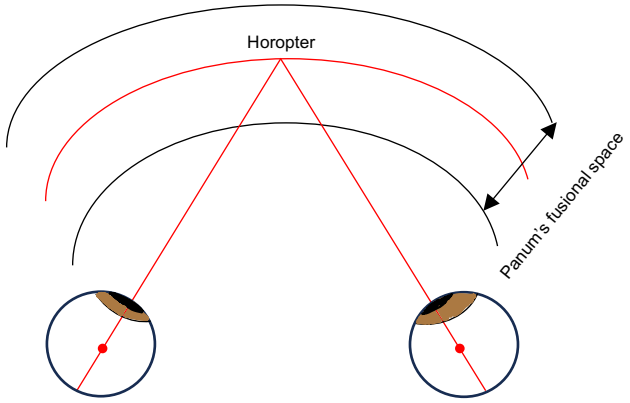


Figure 1.8. A schematic of Panum's fusional space and the horopter.

1.4.2.2.5 Accommodation

Accommodation is the physiological ability of the crystalline lens to changes its focal length, and hence its refractive power, to maintain a clear image of an object over a range of distances (Maddock et al., 1981). Over the years, there have been several theories surrounding the mechanism of accommodation. The most widely accepted theory was proposed in 1855 by Hermann von Helmholtz, which states that when the eye accommodates, the ciliary muscle contracts, which causes the anterior and posterior zonules (which are connected to the capsule and the lens) to relax. Subsequently, the lens diameter decreases resulting in an increased curvature and thickness of the lens (Martin et al., 2005). The accommodative reflex is a three-part reflex that brings near objects into focus through lens thickening, convergence, and pupillary constriction (Fisch, 2015).

Accommodative anomalies can be separated into the following conditions.

1. Accommodative insufficiency

Accommodative insufficiency is the inability of pre-presbyopes to focus, or sustain focus, during near vision tasks (Hussaindeen and Murali, 2020).

2. Accommodative infacility

Accommodative infacility is where the latency and speed of the accommodative response is abnormal compared to normative clinical data (Scheiman et al., 2011).

3. Accommodative excess

Accommodative excess, which is also known as accommodative spasm, is when an individual exerts more accommodation than is required for the visual stimulus, or is unable to relax accommodation (Rutstein et al., 1988).

4. Lag of accommodation

The lag of accommodation is when the accommodative response is less than the accommodative stimulus demand (Jaiswal et al., 2019).

Several studies have measured accommodative parameters before and after digital device use. Contrasting results have been found for the lag of accommodation (which is when the accommodative response is less than the accommodative stimulus demand) when viewing targets on a computer monitor in comparison to paper. Wick and Morse (2002) found the lag of accommodation to be approximately 0.33 D higher when reading from a VDT compared with printed material (Wick and Morse, 2002). Similarly, Hue *et al*. (2014) found a significantly larger lag of accommodation when viewing an iPad in comparison to hardcopy (Hue et al., 2014). When the lag of accommodation exceeds the depth of focus, near vision blur, sore and tired eyes are more likely to be experienced (Jaiswal et al., 2019).

In contrast, when performing dynamic retinoscopy, Penisten *et al*. (2004) found a small, but statistically significant 0.32 D smaller lag of accommodation when reading from a VDT target compared with printed material (Penisten et al., 2004). Other studies found no significant changes in accommodation between the two conditions (Rosenfield et al., 2009, Collier and Rosenfield, 2011, Devenier et al., 2021, Yammouni and Evans, 2021). A 2021 study performed by Yammouni and Evans (2021) found no strong associations between the results of the Wilkins rate of reading test (WRRT), the CVS-Q, and any binocular functions. However, the study did find that patients with an esophoric fixation disparity on the near Mallett unit were more likely to benefit from low-powered near additions, and that DES has a multifactorial aetiology (Yammouni and Evans, 2021).

1.4.2.2.6 Vergence

Convergence is when both eyes turn inwards to fixate an object or image that is closer than the previous fixation point. Conversely, divergence is when both eyes turn outwards to fixate an object or image that is further away than the previous fixation point (Oxford University Press, 2021). The vergence eye movement system is the only visual response which causes disconjugate eye movements (Searle and Rowe, 2016). Much remains to be understood regarding the physiological mechanisms of vergence (Demer and Clark, 2018) but it is believed that vergence eye movements are governed by neural control (Gamlin and Yoon, 2000, Alkan et al., 2011).

Vergence anomalies can be separated into the following conditions.

1. Decompensated heterophoria

Decompensated heterophoria is a failure of the vergence system resulting in a breakdown of a heterophoria to a heterotropia (Dabasia, 2010).

2. Convergence insufficiency

Convergence insufficiency is the inability to maintain fusion whilst looking at a near target. It is usually diagnosed when the NPC is greater than 8-10 cm (Hayes et al., 1998), when an exophoria is greater for near fixation than for distance fixation, and when there is insufficient positive fusional vergence to meet Sheard’s criterion (Goering et al., 2021).

3. Poor vergence facility

Poor vergence facility is when the fusional vergence system struggles to respond rapidly and accurately to changing vergence demands over time (Gall et al., 1998).

4. Convergence excess

Convergence excess is when an esodeviation is greater for near fixation than for distance fixation (Vivian et al., 2002).

5. Divergence excess

Divergence excess is when an exodeviation is greater for distance fixation than for near fixation (Lim et al., 2011).

6. Divergence insufficiency

Divergence insufficiency is when esodeviation is greater for distance fixation than for near fixation (Pineles, 2015).

Several studies have measured vergence parameters before and after digital device use. Nyman *et al*. (1985) did not find a difference in the convergence capacity of VDT operators after 5 hours of VDT work compared to a reference group who did not use a VDT (Nyman et al., 1985). Yeow and Taylor (1989) conducted a similar study and found that VDT work did not have a significantly greater effect on visual function compared to non-VDT work (Yeow and Taylor, 1989). In contrast, Watten *et al*. (1994) found a decrease in the positive and negative relative vergence ability of young female VDT users after an 8-hour workday implying that computer use does affect the ability to converge and diverge appropriately (Watten et al., 1994). In 2011, Collier and Rosenfield found that after 30 minutes of reading on a laptop, DES symptoms were worse in participants exhibiting zero fixation disparity in comparison to participants who had an exo associated phoria. The results of this study suggested that a slightly reduced vergence response increases participant comfort during the task (Collier and Rosenfield, 2011). More recently, Padavettan *et al*. (2021) assessed vergence and accommodation parameters in participants before and after reading N6 print at 40 cm for 30 minutes on a smartphone device. They found a statistically significant worsening of the negative and positive relative accommodation and lag of accommodation, and a statistically significant worsening of negative and positive fusional vergence after smartphone use (Padavettan et al., 2021).

An individual with a binocular vision anomaly is likely to experience symptoms of eye strain during sustained near vision tasks (Rosenfield, 2011). As people are spending many hours viewing digital devices it is unknown whether eye strain symptoms are due to viewing the device or just because a sustained near vision activity is being performed. Nevertheless, to allow people to operate devices in comfort, it is important to manage non-strabismic binocular vision anomalies by correcting ametropia, or by using plus lenses and / or vision therapy (Hussaindeen and Murali, 2020).

1.4.2.3 Pupil size

1.4.2.3.1 Pupillary reflexes

Pupillary reflexes involve the autonomic (Edinger-Westphal) component of the oculomotor nucleus (Heiland Hogan et al., 2021). The pupils are generally equal in size. In the dark, both pupils dilate, and in direct light, both pupils constrict. The consensual reflex is when both pupils constrict, even though only one eye is stimulated. The accommodative reflex causes the pupils to constrict when the eye is focused on a near object (Spector, 1990). Pupil constriction improves depth of focus, which is the perceptual tolerance for retinal defocus and the perception of blur (Ciuffreda et al., 2007). Changes in pupillary characteristics and response have been explored as potential indicators of visual fatigue (Sheppard and Wolffsohn, 2018).

1.4.2.3.2 Pupil size and digital device usage

When reading from screens, the pupils constrict due to the accommodative reflex and screen brightness. Saito *et al*. (1994) found that after 4 hours of computer work, there was a reduction in the near reflex amplitude and a delay in the pupil light reflex (Saito et al., 1994). Miranda *et al*. (2018) found that pupil size reduced up to 20 % when using digital devices compared to print (Miranda et al., 2018), however, reading from screens tends to increase cognitive demands which subsequently causes the pupils to dilate (Querino et al., 2015) and after prolonged periods (2-hours) induces ocular instability (Di Stasi et al., 2013); these conflicting signals may result in visual fatigue (Miranda et al., 2018).

1.4.2.3.3 Pupil size and discomfort glare

Reflective glare can cause discomfort in digital device users. Hopkinson (1956) concluded there was no relationship between pupil diameter and the degree of discomfort from glare (Hopkinson, 1956); this was supported by Fry *et al*. (1975) who reported that pupil size alone does not generate discomfort, rather it is the fluctuation in size which causes the discomfort (Fry and King, 2013). In contrast, Stringham *et al*. (2011) subjected participants to glare by using bright white LEDs. The results showed that greater iris constriction, which results in pupil constriction, caused greater visual discomfort (Stringham et al., 2011).

Discomfort glare is always accompanied by a strong contraction, or spasm in the muscles surrounding the eye, which is commonly referred to as squinting (Murray et al., 2002).

Squinting increases the tension in the orbicularis oculi muscle causing ocular pain and tired eyes (Thorud et al., 2012). Lin *et al*. (2015) subjected participants to glare and recorded the corresponding eye movements and pupil size. The results showed that the subjective evaluation of glare discomfort was highly correlated with the speed of eye movement and pupil constriction, which led to the suggestion that long term exposure to discomfort glare causes visual fatigue and eye strain (Lin et al., 2015).

1.4.2.3.4 Management of discomfort glare

Bright light sources need to be controlled with proper blinds, adjustment of the room arrangement, or by using screens or filters so that an acceptable level of lighting is obtained to minimise visual fatigue (Health and Safety Executive, 2021a).

1. Anti-reflection screens or filters

The primary purpose of anti-reflection (AR) screens or filters is to increase the contrast by decreasing the luminance of the darker colours on the screen. Over the years, there have been several experiments performed to see if AR screens or filters reduce the symptoms of visual fatigue and contrasting results have been found (Chapter 4, Table 4.1).

2. Blue-blocking screens or filters

Concerns have been raised surrounding blue light and its effect on suppressing the sleep-inducing hormone melatonin (section 1.4.1) and its association with retinal phototoxicity (Ham et al., 1976, Jaadane et al., 2015). Although research is currently ongoing within this area, at the time of writing the thesis, there is no evidence to support the use of blue-blocking filters as a clinical treatment for DES (Rosenfield et al., 2020). The UK College of Optometrists reiterates this in their positional statement which states; ‘If Optometrists are selling blue-blocking lenses, they should make their patients aware that there is no strong evidence that blue-blocking spectacle lenses will improve visual performance, alleviate symptoms of eye strain, or improve sleep quality’ (The College of Optometrists., 2022).

3. Privacy screens or filters

Privacy screens or filters are designed to prevent visual hacking and usually start to block visibility at around a 30-degree side angle; at around a 60-degree side angle the screen appears blacked out (Nelson, 2019). In 2020, the privacy screen filters market was valued at 430.32 million USD and by 2026 it is expected to reach 1134.77 million USD (Mordor Intelligence, 2021). At the time of writing, there does not appear to be any published

research measuring the impact of privacy screen filters on DES; the thesis addresses this gap in the literature in Chapters 4 and 5.

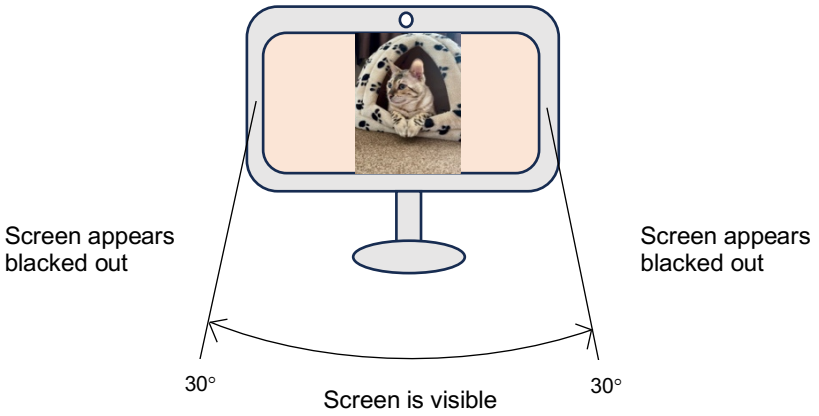


Figure 1.9. Figure showing how a privacy screen filter installed on a desktop computer monitor prevents sideways viewing while providing a clear view for the computer user.

1.4.2.4 Blinking dynamics

A blink is a temporary closure of both eyes (Evinger et al., 1991). The blinking process, especially blink rate, appears to be controlled by the orbitofrontal cortex which is a prefrontal cortex region in the frontal lobes of the brain (Tsubota et al., 1999). Very little is known about the function of the orbitofrontal cortex, but it is thought to be involved in emotional control and cognitive processing (Wallis, 2007).

The orbicularis oculi muscle is in the orbital region of the face and is innervated by the seventh cranial nerve. It receives its blood supply from the ophthalmic artery, which is a branch of the internal carotid artery, and from the maxillary, superficial temporal, and facial arteries which are three branches of the external carotid artery (Tong et al., 2022). The orbicularis oculi is responsible for eyelid closure. The LPS muscle is innervated by the third cranial nerve and receives its blood supply from the ophthalmic artery. The LPS is responsible for eyelid elevation so when the orbicularis oculi is active, the LPS is inhibited (Rucker, 2010). If the eyelids are unable to close, it can result in exposure keratopathy and dry eye (Lee and Lew, 2019).

1.4.2.4.1 Types of eye blinks

1. Spontaneous blinking

Spontaneous blinking occurs subconsciously and accounts for most of the blinks performed during the day. It helps maintain the pre-corneal tear film, ensuring good optical quality, as well as re-wetting the ocular surface, which aids in lubrication and removal of tear film debris (Schulze. M, 2021).

2. Reflex blinking

Reflex blinking, which is also referred to as corneal reflex, is typically triggered by an external stimulus, such as a foreign body, sudden bright light, or a loud noise (Peterson and Hamel, 2021). Its purpose is to help protect the eyes from any potential harm.

3. Voluntary blinking

Voluntary, or consciously performed blinks, are intentional lid movements for a specific purpose, for example to achieve re-wetting of the ocular surface after prolonged eye opening (McMonnies, 2020).

1.4.2.4.2 Blinking dynamics

The control of blinking is thought to reflect complex interactions between maintaining clear and healthy vision, and influences tied to central dopaminergic functions including cognitive states, psychological factors, and medical conditions (Marshall, 2007, Andreu-Sánchez et al., 2017, Hoppe et al., 2018). During certain tasks such as reading and watching videos, blinks occur at breakpoints of attention suggesting a role in information segmentation, but the relationship between cognitive load and blink rate is still not fully understood (Callara et al., 2023). The default mode network (DMN) is a set of brain regions that is least active during cognitive activity and most active during periods of internally focused tasks (Ekhtiari et al., 2016, Liu et al., 2017a). Nakano *et al*. (2013) hypothesised that spontaneous eyeblinks control the disengagement of attention during cognitive tasks by momentarily activating the DMN (Nakano et al., 2013).

1.4.2.4.3 Factors affecting blink rate

1. Cognitive load

The spontaneous eye blink rate (sEBR) varies significantly between individuals from 4 to 26 blinks per minute (Bentivoglio et al., 1997). Several studies have observed a reduction in the

sEBR during reading tasks in both hard copy and computer conditions. As no significant difference in the sEBR has been observed between the two conditions, it has been proposed that changes in blink rate are most likely due to differences in cognitive load rather than the method of task presentation (Chu et al., 2014, Argilés et al., 2015, Rosenfield et al., 2015). It has been suggested that blinks are not executed whilst information is being processed (Wascher et al., 2015), and only occur when the last step of the processing sequence has been completed (Callara et al., 2023). Therefore, a task with a greater cognitive load (which takes longer to process and complete, see Chapter 6) will result in a reduced sEBR, which in turn leads to the development of an unstable tear film and symptoms of dry eye disease.

2. Dopamine and emotional state

Dopamine is a neurotransmitter produced in the brain. It plays a role in pleasure, mood, learning and attention, and other physiological functions (Juárez Olguín et al., 2016). Some studies have suggested that a greater concentration of dopamine results in an increased blink rate (MacLean et al., 1985, Taylor et al., 1999). In contrast, other studies have reported no effects of dopaminergic drugs on blink rate (Ebert et al., 1996, van der Post et al., 2004). Due to contrasting results it remains to be determined whether blink rate can be used as an indicator for specific aspects of dopamine functions (Dang et al., 2017).

3. Fatigue

Fatigue influences normal blinking behaviour (Morris and Miller, 1996). Globally, it has been estimated that between 10 and 20 % of all road crashes are fatigue-related (Brake., 2022). Spontaneous eye blinks are the most promising biosignal for in-car sleepiness warnings with blink duration, blink interval, and standardised lid closure speed being the best indicators of sleepiness (Schleicher et al., 2008). Research is currently ongoing to aid in the development of reliable driver drowsiness detection systems (Schmidt et al., 2018).

4. Ocular surface conditions

Nakamori *et al*. (1997) found that the blink rate and maximum blink interval are dependent on impulses arising from the cornea and conjunctiva. Topical anaesthesia, wind, exposed ocular surface area, dry eye, and screen use all significantly changed the blink rate and maximum blink interval (Nakamori et al., 1997). Wu *et al*. (2014) confirmed this, observing a high correlation between ocular surface sensation and the blink response, whereby an increase in surface stimulation resulted in an increase in the blink response (Wu et al., 2014b).

1.4.2.4.4 Factors affecting completeness of blink

1. Digital screen usage

Unsuccessful inhibition of a spontaneous blink or partial blinks (which are defined as blinks with no contact between the upper and lower eyelids) and a longer eyelid closing phase may result in an incomplete blink (Dartt, 2010, Su et al., 2018). Incomplete blinks approximately double the exposure of the inferior ocular surface resulting in loss of tear film homeostasis, ocular surface dryness, lid wiper epitheliopathy, and visual fatigue (McMonnies, 2007, Jie et al., 2019). Multiple studies have found that digital screen conditions result in a higher percentage of incomplete blinks compared to hard copy conditions (Cardona et al., 2011, Hirota et al., 2013, Chu et al., 2014, Argilés et al., 2015). Chu *et al*. (2014) observed 25 visually normal subjects with a mean age of 25.1. A mean blink rate of 14.9 and 13.6 blinks per minute was measured for the computer and hard copy conditions respectively ($p = 0.58$). However, the computer condition had a significantly higher percentage of incomplete blinks (7.02 vs. 4.33%; $p = 0.02$). The mechanism behind this currently remains unclear (Sheppard and Wolffsohn, 2018). It would not be unreasonable to suggest that the combination of incomplete blinking and a reduced sEBR may account for the dry eye symptoms experienced by digital screen users (Argilés et al., 2015).

2. Lagophthalmos

Lagophthalmos is the incomplete or defective closure of the eyelids resulting in incomplete blinking, corneal exposure, and evaporative dry eye (Pereira and Glória, 2010). There are many aetiologies associated with lagophthalmos such as facial nerve paralysis, sleep, and post-surgery and / or trauma (Fu and Patel, 2022).

1.4.2.4.5 Measuring blink rate and completeness of blink

1. Video recordings

A video camera can be used to record a person blinking over a certain amount of time. The video is then stopped and replayed, and the number of eye blinks, and number of complete blinks performed are counted manually. Although this method is the most accurate, it can be very time-consuming (Jiang et al., 2013).

2. Electromyography

Electromyography (EMG) measures the electrical activity of muscles and nerves. It has been used to study the origin of involuntary eyelid closure, blepharospasm, and the evoked blink reflex (Aramideh et al., 1994, Valls-Sole and Defazio, 2016). Surface EMG mapping of the

orbicularis oculi muscle has been used for real-time blink detection, however, crosstalk from adjacent muscles and the interference of the masseter muscle questions the reliability of the measurements obtained (Frigerio et al., 2014, Rantanen et al., 2016).

3. Electrooculography

Electrooculography (EOG) measures the standing potential between the electrically positive cornea and the electrically negative retina (Humayun et al., 1999). During EOG, electrodes are placed either horizontally or vertically around the eyes, and the differences in potential changes induced by eye movements are detected. Unfortunately, EOG signals are contaminated by physiological artifacts such as jaw clenching or smiling, which can undermine its reliability (Belkhiria and Peysakhovich, 2020).

4. Pupillometry

Pupillometry measures the fluctuations in pupil diameter in response to cognitive processing (Trevethan and Sahraie, 2009). As the pupils constrict and re-dilate within a few seconds after each eye blink (Yoo et al., 2021), several studies have used eye tracking software with an automated algorithm which measures the occlusion of the pupil, by rate of change in pupil diameter and by vertical displacement of the measured pupil centre, to detect and measure the number of eye blinks performed within a certain period of time (Schulze. M, 2021, Ranti et al., 2020). In the study performed by Shultz *et al*. (2011), compared with video recordings, the algorithm accurately detected 95 % of all blinks identified by manual coding of video images, and compared with EMG, the algorithm accurately detected 96.4 % of blinks (Schulze. M, 2021).

1.4.2.4.6 Management of blink disorders

1. Blinking exercises

Meibum is a lipid-rich secretion which is produced by the meibomian glands. During a complete blink, meibum is released from the glands and dispersed over the ocular surface (Bron et al., 2004). Meibomian gland dysfunction (MGD) is an inadequate release of meibum which results in similar symptoms to dry eye. Incomplete blinking and a reduction in the sEBR during screen use has been associated with MGD (Wu et al., 2014b) and evaporative dry eye (Rosenfield et al., 2015). Increased blinking has not been found to alter symptoms during a computer task (Acosta et al., 1999) but more recent research has found that blinking exercises consisting of gently closing the eyes for 2 seconds, opening the eyes, closing the eyes for 2 seconds, followed by squeezing the eyes closed for 2 seconds

significantly reduced dry eye symptoms and improved TBUT by modifying poor blinking patterns (Kim et al., 2021).

2. Wink glasses

In 2009, Masunaga Optical Manufacturing launched ‘wink glasses’. A sensor attached to the spectacle lenses detected blinking movements. If a blink was not detected for more than five seconds, the lenses fogged up by gradually making the LCD over one eye turn opaque; this forced the user to blink to make the lenses clear again. Ang *et al*. (2014) found that wink glasses increased post-task tear stability, increased blinking rate, and reduced ocular surface symptoms during computer use amongst young and healthy adults (Ang et al., 2014). At the time of writing, wink glasses appear to be unavailable to purchase.

3. Blink animation software

Blink animation software has been developed to try and encourage blinking and aid in the alleviation of dry eye symptoms. Nosch *et al*. (2015) found that ‘blink blink’ software, which prompts a double blink by using an on-screen animation, improved blink rate and dry eye symptoms in twenty participants (Nosch et al., 2015). Ashwini *et al*. (2021) tested the efficacy of the ‘blink blink’ software in computer users, whose screen time was greater than four hours per day, and who also suffered with dry eye disease, and found that eight reminders per minute increased the blink rate and improved dry eye related symptoms (Ashwini et al., 2021).

1.4.2.5 Dry eye disease

The human tear film is approximately 3-4 micrometres (μm) thick (King-Smith et al., 2000, Dartt and Willcox, 2013). It covers both the cornea and conjunctiva and forms a meniscus at the posterior margins of both eyelids. The action of blinking spreads tears medially across the anterior eye surface which helps maintain a smooth optical surface and enables removal of metabolic waste products (Pflugfelder and Stern, 2020). The traditional description of the tear film divides it into three layers however it is now widely accepted that the tear film comprises of a thin superficial lipid layer, a thicker aqueous- mucin phase, and a glycocalyx layer that is bound to the ocular surface epithelium (Downie et al., 2021).

1.4.2.5.1 Layers of the tear film

The meibomian glands are a type of sebaceous gland that line the upper and lower eyelids in a single row. There are approximately 30-40 glands in the upper eyelid and 20-30 glands

in the lower eyelid (Utheim et al., 2014). The meibomian glands secrete the lipid layer; this is the most superficial layer of the tear film and is approximately 40 nanometres (nm) thick, ranging from 15 to 157 nm (King-Smith et al., 2010). The action of blinking spreads the lipids over the ocular surface which helps prevent tear evaporation and provides a smooth optical surface for the cornea (Bron et al., 2004).

The aqueous-mucin phase is the thickest component of the tear film. The aqueous fluid is produced by the lacrimal glands, which are in the orbits, and the accessory lacrimal glands (glands of Krause and Wolfring) which are in the conjunctiva (Golden et al., 2022). The tears and tear proteins provide lubrication, nutrition, and protection to ocular surface tissues (Cwiklik, 2016). Mucins are produced by the conjunctival goblet cells and conjunctival epithelial cells (Hodges and Dartt, 2013). Mucins lubricate the ocular surface and provide a protective barrier to prevent pathogens and debris binding to the cellular surface (Bron et al., 2004).

The corneal and conjunctival epithelium is covered with microvilli and microplicae, and these are covered by a glycocalyx layer which is composed of glycoproteins and glycolipids (Davidson and Kuonen, 2004). The glycocalyx layer is the boundary between the epithelium and the tears, and plays a role in epithelial surface lubrication, hydration, and protection from pathogens and debris (Uchino, 2018).

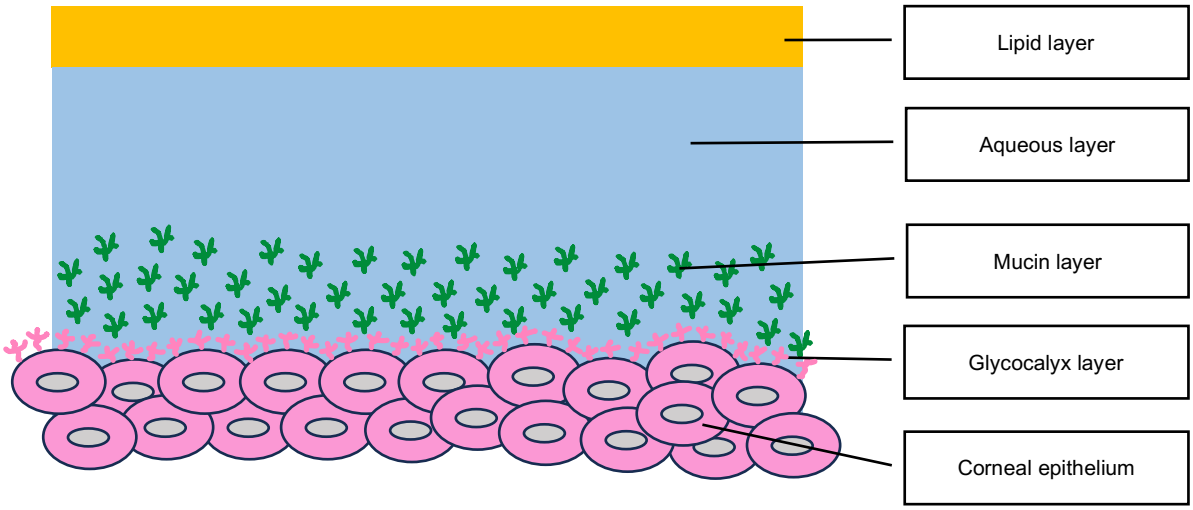


Figure 1.10. Basic schematic of the human tear film.

1.4.2.5.2 Types of tears

1. Basal tears

The sympathetic nervous system is thought to stimulate basal tear secretion from the accessory lacrimal glands (Jones, 1966). Basal tears maintain ocular surface hydration and comfort, provide nutrients to the ocular surface, and helps flush away debris (Chang and Purt, 2022).

2. Reflex tears

Mechanical stimulation of the ocular surface activates the trigeminal nerve - brainstem - facial nerve - main lacrimal gland reflex arc, resulting in the production and secretion of reflex tears (Willcox et al., 2017). Reflex tears enable the removal of foreign bodies and chemicals from the ocular surface (Murube, 2009).

3. Psycho-emotional tears

Psycho-emotional tears, which are commonly known as crying, are produced upon emotional stimulation such as extreme happiness or sadness and are secreted by the lacrimal gland. Charles Darwin claimed that the function of crying is ‘purposeless’ (Darwin, 1872) but modern-day research has suggested crying provides catharsis and a signalling to others that support is needed (Vingerhoets, 2013, Vingerhoets and Bylsma, 2016).

1.4.2.5.3 Dry eye

The TFOS DEWS II report (2017) redefined dry eye as “a multifactorial disease of the ocular surface characterised by a loss of homeostasis of the tear film, and accompanied by ocular symptoms, in which tear film instability and hyperosmolarity, ocular surface inflammation and damage, and neurosensory abnormalities play etiological roles” (TFOS, 2017). Dry eye disease (DED) sufferers experience a range of symptoms including foreign body sensation, tearing, ocular discomfort, photophobia, itching, fatigue, and visual disturbance. All these symptoms negatively impact on quality of life.

1.4.2.5.4 Screen use and dry eye

During screen use there are three main factors which are considered responsible for contributing to dry eye symptoms, these are blinking characteristics (section 1.3.1.4), gaze angle, and room humidity.

As mentioned in section 1.1.5.1, when viewing smaller displays such as laptops, tablets, smartphones, or reading hardcopy text, the eyes are usually in the downward gaze position; this reduces the exposed ocular surface area, and/or the need for blinking (Wolffsohn et al., 2023). When viewing larger displays such as televisions and desktop computers, the eyes are usually in, or just slightly below, the primary gaze position; this higher viewing angle exposes a greater ocular surface area which can thin the lipid layer, alter the mucin layer, and reduce tear film stability resulting in an increased rate of tear film evaporation (Rosenfield, 2011). Several studies have found that a viewing distance of 90 cm and slight downward gaze of 10-20° aids in the reduction of asthenopia and ocular discomfort when using digital displays although interpersonal variability is expected (Nathan et al., 1985, Menozzi et al., 1994, Tsubota and Nakamori, 1995, Jaschinski et al., 1998, Jaschinski et al., 1999b, Pansell et al., 2007, Nielsen et al., 2008, Mehra and Galor, 2020, Kaur et al., 2022, Pavel et al., 2023).

Many office-based computer screen users are exposed to low humidity conditions caused by ventilation fans and air conditioning units. Low humidity causes tear evaporation and thinning of the tear film, resulting in dry eye symptoms (Abusharha and Pearce, 2013, Wolkoff, 2017). Optimal room humidity levels range from 40 % to 55 %, mainly due to effects on upper airway health and respiratory function (Wolkoff and Kjaergaard, 2007, Razjouyan et al., 2020).

1.4.2.5.5 Symptomatic assessment of dry eye

Over the years, many different dry eye questionnaires have been developed. The TFOS DEWS II Diagnostic Methodology report recommends the use of either the Ocular Surface Disease Index (OSDI) questionnaire or the 5-item Dry Eye Questionnaire (DEQ-5) when assessing dry eye symptomology (Wolffsohn et al., 2017).

The OSDI questionnaire assesses subjective dry eye symptoms and the impact of dry eye on vision-related activities of daily life within the previous week (Schiffman et al., 2000). It comprises of three subscales: ocular symptoms (three questions), vision-related functions (six questions), and environmental triggers (three questions). Each question is answered on a five-point scale ranging from ‘none of the time’ to ‘all of the time’. The OSDI total score ranges from 0 to 100 points and is obtained by multiplying the total score of all the questions by 25 and dividing the result by the number of valid answers. The total score can then be used to classify the respondent’s dry eye symptoms as normal (0-12 points), mild (13-22 points), moderate (23-32 points), or severe (33-100 points), where ≥ 13 (out of 100)

indicates dry eye (Schiffman et al., 2000, Ozcura et al., 2007). The OSDI has good validity, test-retest reliability (ICC = 0.70 - 0.82), and consistency (Schiffman et al., 2000, Grubbs et al., 2014) however, it does not assess the severity of symptoms and has either no, or a very slight correlation, with clinical parameters (Schmidl et al., 2015). Nevertheless, it is the most frequently used symptomology questionnaire in dry eye research (Dougherty et al., 2011).

The DEQ-5 consists of five questions that assess the frequency of watery eyes, discomfort and dryness and late day intensity of discomfort and dryness (Chalmers et al., 2010). The DEQ-5 can discriminate dry eye and non-dry eye patients, Sjogren's syndrome dry eye and non-Sjogren's syndrome dry eye and groups with varying dry eye severity. The proposed screening criteria for the DEQ-5 are ≥ 6 (out of 22) for dry eye and > 12 for suspected Sjogren's syndrome (Chalmers et al., 2010). Although the DEQ-5 is an accepted dry eye questionnaire, its validity and reliability have not been verified (Okumura et al., 2020).

1.4.2.5.6 Dry eye management

There are two recognised forms of DED; aqueous deficient (reduced tear secretion; this is relatively rare and related to autoimmune diseases) and evaporative (dysfunctional tear film), however individuals can have both; a combination of aqueous deficient and evaporative. Determining the major cause(s) of an individual's DED is critical in helping select the most appropriate management strategy (TFOS, 2017). Treatment for DED usually follows a stepwise approach beginning with education, dietary modifications, local environmental considerations, eyelid treatments, and then progressing onto pharmacological and non-pharmacological interventions. As blinking dynamics are affected during screen use, blink training may also be a very helpful management strategy against symptoms of dry eye and DES (Sheppard and Wolffsohn, 2018).

1. Dietary modifications

The human body cannot synthesise essential fatty acids (EFAs) so they must be ingested from dietary sources (Di Pasquale, 2009). Common food sources include flaxseeds, walnuts, chia seeds, soybean oil, and high concentrations of oily fish (TFOS, 2017). EFAs have a broad range of systemic anti-inflammatory effects (Purasiri et al., 1997) and can influence the quality and quantity of intracellular lipids (Liu et al., 2016) however, the role of EFA supplementation for treating DED is not yet completely understood (TFOS, 2017).

Lactoferrin is a tear glycoprotein with anti-inflammatory, antimicrobial, and antioxidant properties. Reduced tear fluid lactoferrin levels have been reported in DED sufferers (Danjo

et al., 1994, Versura et al., 2010, Sonobe et al., 2019). Oral lactoferrin supplementation has been shown to improve dry eye symptoms (Dogru et al., 2007, Devendra and Singh, 2015) but the efficacy of lactoferrin is yet to be confirmed in its potential application in the field of DED (Vagge et al., 2020).

Whole-body hydration appears to be a consideration in DED (Walsh et al., 2012) however, more research is needed before recommending whole body hydration with fluid intervention as a treatment for DED (TFOS, 2017).

2. Local environment considerations

The most frequently used preservative in topical drugs, benzalkonium chloride (BAK), is known to irritate the ocular surface due to its toxic effects (Baudouin et al., 2010). Clinical trials have shown that by changing to preservative-free (PF) topical drugs, patients experienced significantly fewer signs and symptoms of ocular surface disease (OSD) (Pisella et al., 2002, Jaenen et al., 2007, Jee et al., 2014). Drugs used for treating systemic chronic illnesses such as antihistamines, beta-blockers, antidepressants, diuretics, anxiolytics, antipsychotics, anti-Parkinsonian drugs, isotretinoin, oestrogen therapy, and systemic chemotherapy can contribute to DED (Wong et al., 2011). To reduce or eliminate unwanted side effects, strategies include changing the route of drug administration from oral to topical, adjusting the drug dosage, discontinuing certain drugs and switching to another medication, or implementing more aggressive DED management (Gomes et al., 2017). Contact lens wear can contribute to ocular discomfort and DED. Management strategies include altering the contact lens design, increasing the contact lens replacement frequency (i.e. switching from monthly contact lenses to 2-weekly contact lenses), changing or discontinuing the care system, using tear supplementation, and considering punctal occlusion (Papas et al., 2013). Although contact lens wear is associated with DED, it can be used in the management of more severe forms of DED. Therapeutic soft contact lenses, which are also known as bandage contact lenses, can be worn as daily wear or extended wear, however the latter is associated with an increased risk of microbial keratitis (Stapleton et al., 2008). Rigid gas permeable scleral lenses appear to be well tolerated for use in severe DED (Bavinger et al., 2015) but further investigation on the physiological impact of scleral lens wear on the ocular surface is required (Schornack, 2015).

Prolonged exposure to low humidity, increased or decreased air temperature, air movement, pollutants, and tobacco smoke can all result in DED (Abusharha and Pearce, 2013). Management strategies include artificial tears, anti-inflammatory medications, humidifiers,

punctal plugs, and smoking cessation (Willis et al., 1987, Satici et al., 2003, Hirayama et al., 2013).

3. Eyelid treatments

Anterior blepharitis, also known as anterior lid margin disease, is usually a direct result of bacterial infection, but can also be caused by a disorder of the ciliary sebaceous glands of Zeis. Short-term topical antibiotics reduce the bacterial load on the lid margin (Jackson, 2009) and low concentrations of tea tree oil can be used to reduce the number of demodex on the eyelashes by 5 % to 50 % without causing ocular irritation (Savla et al., 2020). Lid hygiene procedures are an effective treatment for anterior blepharitis but compliance amongst patients is notoriously poor (Alghamdi et al., 2017).

Posterior blepharitis, also known as posterior lid margin disease, is where bacterial lipases break down meibomian lipids resulting in abnormal meibomian secretion and an unstable tear film. MGD, which is commonly characterised by terminal duct obstruction and / or qualitative / quantitative changes in the glandular secretion of the meibomian glands, is the most common cause of posterior blepharitis (Nelson et al., 2011). MGD can be treated through a variety of methods which are described below.

a) Warm compresses

Warm compresses such as hot towels or microwavable bags containing seeds or beads are applied to the outer lid for a minimum of 5 minutes. Optimal warm compress treatment is achieved when the palpebral conjunctiva and meibomian glands reach a temperature ≥ 40°C (Murakami et al., 2015). At this temperature the secretions in obstructed glands are softened or liquefied, which results in an improvement in symptoms, NIBUT, and LLT of the tear film (Bilkhu et al., 2014).

b) Manual expression

Manual expression of the meibomian glands is achieved by forceful squeezing of the eyelids by the examiner’s fingers or by a rigid object such as a metal paddle. Although this method appears to be effective in treating MGD (Wang et al., 2018b, Aketa et al., 2019) pain is the limiting factor as the tolerable force of up to 15 pound-force per square inch (PSI) is usually inadequate to express obstructive material (Korb and Blackie, 2011).

c) Intense pulsed light

Intense pulsed light (IPL) delivers intense pulses of non-coherent light from 500 nm to 1200 nm via a hand held computer-controlled flashgun (TFOS, 2017). The mechanisms of action

of IPL treatment are not fully understood but it appears to be a safe procedure which improves OSDI symptomology, TBUT, and meibomian gland functionality (Tashbayev et al., 2020, Barbosa Ribeiro et al., 2022).

d) Intraductal probing

Intraductal probing is performed under local anaesthesia and involves inserting a sterile probe into the ducts of the meibomian glands; this expands the ducts, lowers the intraglandular pressure, and restores normal gland secretion (Maskin, 2010). As intraductal probing has not been shown to outperform placebo (Kheirkhah et al., 2020) further studies are required to establish if intraductal probing provides any lasting improvement of DED and MGD (Magno et al., 2021).

e) Lid debridement

Lid debridement mechanically removes accumulated debris and keratinised cells from the eyelid margin resulting in an increased flow of meibum into the tear film. It has been shown to improve symptoms and meibomian gland function when used as a standalone treatment (Korb and Blackie, 2013, Ngo et al., 2015) and when used in combination with meibomian gland expression (Moon et al., 2021).

4. Tear replacement

A wide range of artificial tears / tear substitutes are commercially available. The most abundant component in lubricant eye drops is the aqueous base (TFOS, 2017) but lipid containing eye drops are also available and have been shown to improve signs and symptoms of dry eye (Craig et al., 2010, Simmons et al., 2015). A variety of viscosity enhancing agents are used to help improve tear film thickness, tear retention and protection of the ocular surface, ocular lubrication, and to help alleviate dry eye symptoms (Wegener et al., 2015). Low-viscosity eye drops are recommended for daytime use whereas high viscosity eye drops / ointments are usually recommended for overnight use as they can cause debris on the eyelids and lashes and transient visual disturbances.

The author of the thesis co-authored a published peer-reviewed paper entitled ‘Artificial Tears: A Systematic Review’ (Semp et al., 2023). The results of the systematic review showed that there is good evidence that artificial tears improve symptoms of DED within a month of regular use, applied ~4x a day, but signs of DED generally take several months to improve. However, not all patients with DED benefit from artificial tears, so if there is no benefit over a month, alternative management should be considered. Combination formulations are more effective than single active ingredient artificial tears. Polyethylene

glycol (PEG) containing artificial tears are more effective than those containing Carboxymethylcellulose (CMC) / carmellose sodium and hydroxypropyl methylcellulose (HPMC). Patients classified as having evaporative DED, benefit from artificial tears with liposomes, especially of higher concentration (Semp et al., 2023).
Raised tear osmolarity is associated with DED however relatively few studies have investigated the impact of hypo- or hyper-osmolar drops on tear osmolarity and DED (TFOS, 2017). Osmoprotectants balance the osmotic pressure without disturbing cell metabolism (Garrett et al., 2013). Trehalose is a naturally occurring osmoprotectant and has been shown to reduce conjunctival inflammation in DED (Li et al., 2012). Mateo-Orobia *et al*. (2021) studied peri- and post-menopausal women; after 3 months of using artificial tears containing trehalose and hyaluronic acid a significant improvement was observed in conjunctival hyperaemia, corneal and conjunctival staining and TBUT (Mateo-Orobia et al., 2021).

Oxidative stress damages the ocular surface and plays an important role in the mechanism of DED (Dogru et al., 2018). Tear fluid contains several antioxidants (Ohashi et al., 2006). Several studies have shown that patients with autoimmune disease and DED have elevated levels of oxidative stress biomarkers in comparison to control groups (Avalos et al., 2007, Giusti et al., 2007, Bohanec Grabar et al., 2009, Choi et al., 2016). Topical / systemic use of antioxidants may have a promising future in the treatment of dry eye disease (Dogru et al., 2018).

Serum is the fluid component of blood obtained after coagulation. The manufacture of serum eye drops involves extracting blood from either the patient (autologous) or healthy donors (allogeneic). Advantages of serum eye drops are their biomechanical and biochemical properties are like normal tears and they are by nature non-allergenic (Geerling et al., 2004, Pan et al., 2017). Franchini *et al*. (2019) conducted a systematic review and meta-analysis of serum eye drops in 729 patients. Short-term benefits in TBUT and OSDI scores were observed but the quality of the evidence was low (Franchini et al., 2019). Umbilical cord serum has also been shown to improve symptom scores, TBUT, corneal fluorescein staining, and impression cytology findings in DED patients (Yoon et al., 2007). The widespread use of serum is limited by a number of factors including legal regulations which differ significantly between countries, production issues, product storage, and high manufacturing costs (TFOS, 2017). Another potential treatment for DED are platelet-rich plasma drops. Although they have been shown to produce a general improvement in symptoms (Alio et al., 2007, López-Plandolit et al., 2011), further evaluation of the efficacy of these drops is required (Nadelmann et al., 2021).

5. Tear conservation

Punctal occlusion blocks the tear drainage system to help preserve natural tears on the ocular surface. The most common method for punctal occlusion is the use of punctal plugs; these can either be temporary or permanent. Punctal plug usage is commonly associated with epiphora and that the improvements in signs and symptoms of DED are inconclusive (Ervin et al., 2017). If punctal plugs cannot be tolerated, permanent surgical closure of the punctum can be considered. There are several surgical methods available. Cauterisation appears to significantly improve DED signs and symptoms but again, epiphora can be a problem (Yaguchi et al., 2012).

Moisture chamber spectacles provide a humid environment which minimises airflow over the ocular surface to slow tear evaporation. Moisture chamber spectacles appear to improve dry eye symptomatology, tear stability, and blink rates in adverse environmental conditions (Ogawa et al., 2018). Ren *et al*. (2018) conducted a study on 22 VDT-associated dry eye participants who use VDTs for over 4 hours per day. The participants wore warming moist chamber goggles for 15 minutes and measures were taken at 5, 30, and 60 minutes after treatment. The study found that the short-term use of warming moist chamber goggles improved ocular comfort, and increased the tear meniscus height (TMH), non-invasive break-up time (NIBUT), and lipid layer thickness (LLT) (Ren et al., 2018). Although the results of this study are promising, further studies are required to investigate the therapeutic value of these devices.

6. Anti-inflammatory agents

Experimental studies in animal models have shown that topical corticosteroids are effective in breaking the unwanted immune responses in DED but they can induce unwanted side effects such as ocular hypertension, cataracts, and infections (Gaballa et al., 2021). Non-steroidal anti-inflammatory drugs (NSAIDs) have been shown to improve DED symptoms (Aragona and Di Pietro, 2007) but they have been known to cause corneal melt (Rigas et al., 2020). NICE state that the immunosuppressant, ciclosporin, is recommended as a possible treatment for severe keratitis in adult patients with DED that has not improved despite treatment with artificial tears (NICE, 2015), however, the effects of ciclosporin on ocular discomfort and ocular surface and tear film parameters is inconsistent and requires further study (de Paiva et al., 2019).

7. Complementary treatments

In several studies, acupuncture has been reported to improve dry eye symptoms, Schirmer scores, TBUT, and corneal staining (Shin et al., 2010, Kim et al., 2012, Yang et al., 2015). It

has been suggested that acupuncture can be used as an adjunctive treatment but more work is needed to optimise the treatment regime (Dhaliwal et al., 2019).

The use of honey to treat wounds and gastrointestinal diseases traces back to the ancient Egyptians, Assyrians, Chinese, Greeks, and Romans (Zumla and Lulat, 1989) but it was not until the late 19th century where its antibacterial properties were first recognised. Since then, honey has also been shown to have antimicrobial, antifungal, and antiviral properties (Anand et al., 2019, Almasaudi, 2021). Manuka honey eye drops have been shown to reduce the number of bacteria isolated from the eyelid margin and conjunctiva in patients with DED and blepharitis (Albietz and Lenton, 2006, Craig et al., 2020) and have also been shown to significantly improve signs and symptoms in meibomian gland dysfunction (Li et al., 2022).

8. Surgical intervention

In rare cases, severe dry eye may require surgical intervention. Conjunctivochalasis is a condition characterised by loose, redundant, and non-oedematous bulbar conjunctiva that can induce tear film instability and disruption to the tear drainage pathway. Its prevalence increases with age (Zhang et al., 2011, Marmalidou et al., 2018). Surgical intervention is considered if ocular lubricants, topical ciclosporin, or punctal occlusion fail to alleviate symptoms. After surgery, patients tend to report an improvement in dry eye symptoms (Ji et al., 2021). In absolute aqueous-deficient dry eye, when all other means have failed, transplantation of the major salivary glands may be considered to provide substitute lubrication (TFOS, 2017). Whilst this procedure is capable of improving comfort, ocular surface reconstruction remains unsuccessful due to the salivary nature of the new tear film (Geerling and Sieg, 2008).

1.4.3 Non-ocular risk factors for digital eye strain

Non-ocular risk factors for DES can be split into 3 categories: workplace ergonomics and musculoskeletal disorders, screen time and visual psychophysics (contrast sensitivity and critical flicker-fusion).

1.4.3.1 Workplace ergonomics and musculoskeletal disorders

Prolonged sitting at ergonomically poor workstations has long been associated with the occurrence of musculoskeletal disorders which affect the muscles, joints, and tendons (Bammer and Martin, 1988, Ong et al., 1995, Wahlström, 2005, Borhany et al., 2018, Mowatt et al., 2018). Approximately 1.71 billion people globally have musculoskeletal conditions

(Cieza et al., 2021) and although the prevalence increases with age, younger people are also affected with low back pain being the main reason for a premature exit out of the workforce (World Health Organisation., 2021a). In 2022/23, 473,000 workers in the UK suffered from work-related musculoskeletal disorders, with the main causes being cited as manual handling, working in awkward or tiring positions, and keyboard or repetitive work. In the same time period, work-related musculoskeletal disorders accounted for 27 % of all work-related ill health (Health and Safety Executive, 2023).

When using a VDU, the position and height of the chair, monitor, keyboard, and mouse are all important factors to consider (van Vledder and Louw, 2015). As previously mentioned, the use of bifocals and general-purpose PALs whilst viewing a VDU can lead to unnatural head positions, resulting in neck and back pain. To reduce the risk of developing these symptoms, occupational lenses, or single vision lenses may be used instead (Balci and Aghazadeh, 1998, Basrai and Aghazadeh, 2004, Becker et al., 2007).

Breaking up long spells of computer work helps prevent fatigue, eye strain, upper limb problems, headaches, and back pain (Borhany et al., 2018). According to the UK Health and Safety Executive (HSE), there is no legal guidance about how long and how often breaks should be for DSE work, but, taking short breaks often, for example 5 to 10 minutes every hour, is advisable (Health and Safety Executive, 2021b). The American Optometric Association promotes the 20/20/20 rule (a 20 second break every 20 minutes to view a distant object at 20 feet) to help alleviate DES (American Optometric Association, 2021). Alghamdi *et al*. (2020) found that participants who followed the 20/20/20 rule for 20 days had positive changes in their dry eye symptoms (CVS-Q and DEQ-5) and a significant increase in their tear break up time (Alghamdi and Alrasheed, 2020). Talens-Estarelles *et al*. (2022) also demonstrated that the 20-20-20 rule is an effective strategy for reducing DES (CVS-Q) and dry eye (OSDI and SANDE) symptoms (Talens-Estarelles et al., 2022a).

1.4.3.2 Screen time

Screen time describes the amount of time spent viewing or using digital devices with a display screen. Research has shown that there is a relationship between the hours spent on digital devices and the severity of both, dry eye (Uchino and Schaumberg, 2013, Uchino, 2018, Hanyuda et al., 2020) and DES symptoms experienced. In respect to DES, symptoms can occur as early as 20-minutes after viewing a digital device (Cardona et al., 2011) but symptoms tend to worsen after 4-hours of digital device usage (Wu et al., 2014a, Choi et al., 2018, Artime Ríos et al., 2019, Touma Sawaya et al., 2020, Gammoh, 2021). Chu *et al*.

(2023) found that participants with baseline smartphone usage of ≥ 4 hours per day had a significantly higher baseline total DES score than those with a baseline smartphone usage of up to 1-hour per day. The study also found that participants with a baseline smartphone usage of 3-4 hours per day had a significantly higher 12-month follow-up total DES score than those with baseline smartphone usage of up to 1-hour per day (Chu et al., 2023).

1.4.3.3 Visual psychophysics

Psychophysics is the study of physical stimuli and their interaction with the sensory systems (Gabbiani and Cox, 2010). In relation to vision, light enters the eye and retinal photoreceptors convert light energy into electrical signals. After further processing within the retina, the electrical signals are transmitted to neurones of the lateral geniculate nucleus (LGN) which is located within the thalamus (Watson, 2012). The LGN has six layers, and neurones within the LGN have receptive fields that are centre/ surround, just like retinal ganglion cells (University of Minnesota, 2020). Visual information is conveyed by two parallel pathways: the magnocellular (M) and parvocellular (P) pathways. The inner two layers of the LGN are M layers. The M pathway is achromatic and carries information about low spatial frequency and high temporal frequency; it is rapid and transient. The outer four layers of the LGN are P layers. The P pathway is chromatic and carries information about high spatial frequency and low temporal frequency; it is slow and sustained (Meissirel et al., 1997). The LGN then distributes the information into the primary visual cortex where visual information is processed (Watson, 2012). The visual system breaks an image down into different cues, such as depth, motion, or colour, and then binds them back together to form percepts of the world (Lu, 2014).

1.4.3.3.1 Contrast sensitivity function

Contrast sensitivity is a measure of the amount of contrast required to detect or discriminate an object. The contrast sensitivity function (CSF) describes an observer's spatial vision abilities and has traditionally been measured using sinusoidal gratings of different spatial frequencies (Cambridge Research Systems, 2020). The human visual system can detect spatial frequencies up to about 60 cycles per degree (cpd). There is no lower limit, but generally measurements are not made below 0.1 cpd due to practical limits of display size (National Research Council Committee on, 1985).

The human visual system experiences difficulty at very low, and very high contrasts (Stone et al., 1980, Kim and Jeong, 2014). Asthenopia has been associated with reading under low

contrast conditions (Gowrisankaran et al., 2012, Glimne et al., 2020) and some migraine sufferers have reported that high contrast striped patterns can trigger migraine attacks (Shepherd, 2000). Lower contrast sensitivity in healthy individuals is associated with increasing age, hyperopia, photopic conditions, and a small pupil diameter (Karatepe et al., 2017).

In 1988, a study tested the threshold for detecting sine wave contrast gratings before and after reading text on a CRT screen, as well as reading from printed paper, for 30-minutes. The results showed small, but statistically significant, decreases in the CSF at low and high spatial frequencies after reading text on the CRT screen. Reading from printed paper produced no change (Mikealian, 1988). At the time of writing, there does not appear to have been any research investigating the effect of modern-day digital devices, and their usage patterns, on contrast sensitivity. As contrast sensitivity can reflect cognitive function (Ridder et al., 2017), measuring it before and after digital device usage may give an insight into the impact of modern-day devices on mental workload.

1.4.3.3.2 Critical flicker-fusion frequency

The critical flicker-fusion frequency (CFF) is the lowest frequency at which a flickering light is perceived as continuous. It is assumed that the CFF can reflect the basic temporal function of the visual system and is therefore a good measure of its performance (Eisen-Enosh et al., 2017). The ability to detect flicker-fusion is dependent on several internal and external factors, and may also be influenced by task time (Chi and Lin, 1998). Internal factors include age, sex, personality traits, circadian variation in brain activity, fatigue, and cognitive functions such as visual integration, visuomotor skills, and decision-making processes (Umeton et al., 2017, Balestra et al., 2018). External factors include the frequency and amplitude of the modulation, the luminance, colour, viewing distance and size of the stimulus, and the retinal location (Shams et al., 2002).

P pathway (chromatic) flicker-fusion thresholds are between the range of 10 to 15 Hz, whereas M pathway (achromatic) flicker-fusion thresholds are between 35 to 60 Hz (Mewborn et al., 2015, Brown et al., 2018). For many years it was believed that the human eye could only detect flicker up to 90 Hz, however, Davis *et al*. (2015) found that humans can perceive visual flicker artifacts at rates over 500 Hz when a display includes high frequency spatial edges (Davis et al., 2015).

Several methods can be used to measure the CFF; these include the method of constant stimuli (MCS), the staircase method (SM), the method of adjustment (MOA) and the method of limits (MOL) (Eisen-Enosh et al., 2017). In the MCS, several values of the stimuli are presented many times, in a random order, by the experimenter for comparison with the standard, and the frequency of the different responses made by the participant is counted. In the SM, a variable stimulus is presented repeatedly and is adjusted upwards whenever it is not perceived and downwards whenever it is perceived (Vickers, 1979). In the MOA, participants control the level of the stimulus, rather than having it be controlled by the experimenters. In the MOL, the stimulus is presented at a high level and is gradually decreased until the participant can no longer perceive it (Eisen-Enosh et al., 2017).

Subjective measures such as questionnaires may be thought of as an opinion rather than fact (Hamilton et al., 2017). It would therefore be of value for researchers to have a valid objective measure of DES to provide robust and meaningful measurements in clinical trials and for patient management. Currently there are no widely accepted objective measures of DES. As CFF is a recognised measure of fatigue and mental workload (Thackray, 1985, Luczak and Sobolewski, 2005) it would not be unreasonable to suggest that changes in flicker-fusion values could be used as an objective measure of DES. Two of the most recently published studies that have investigated the association between DES symptoms and CFF found no significant correlation between these measures (Yan and Rosenfield, 2022, Singh et al., 2023); previous studies investigating the relationship between DES symptoms and CFF are reviewed in Chapter 3 (Table 3.1).

1.5 Other health risks associated with digital device usage

1.5.1 Sleep deprivation

Humans spend about one third of their life sleeping (Aminoff et al., 2011). Sleep is a complex biological process that is not entirely understood (Harvard Medical School., 2007). The pineal gland, which is in the epithalamus near the centre of the brain, receives information about the diffuse light intensity of the environment. It uses this information to produce and secrete the sleep-promoting hormone melatonin (Vigh et al., 2002).

Blue light has been shown to induce melatonin-suppressing responses (Lockley et al., 2003, Chinoy et al., 2018). Digital devices emit blue light and the use of devices one hour before bed has been shown to suppress blood levels of melatonin (Cajochen et al., 2011, Chang et

al., 2015). More recent studies have found that amongst child and adolescent populations, spending multiple hours each day on digital devices is associated with short sleep duration (Hale and Guan, 2015, Twenge et al., 2019, Lund et al., 2021). A 2015-2016 study performed in Finland on 736 children aged 3-6 years found that an hourly increase in total screen time was associated with an 11-minute later bedtime, and a 10-minute shorter sleep duration (Hiltunen et al., 2021).

Sleep problems in early life increase the likelihood of developing obesity and abnormal mental states such as behavioural and emotional issues (Cappuccio et al., 2008, Sadeh et al., 2014). In 2021, a systematic literature review concluded that since blue light may disrupt the circadian rhythm, the use of blue-blocking spectacle lenses / filters in the evening is a viable intervention to recommend to patients with insomnia or a delayed sleep phase (Hester et al., 2021).

1.5.2 Obesity

In 2020, UK adults spent an average of 45 hours each week viewing a digital device (Wood, 2020). Evidence suggests that children and adults increase their eating habits while viewing screens as they are exposed to high-calorie, low-nutrient food (Falbe et al., 2014) and beverage advertising which influences their consumption habits (Robinson et al., 2017). Combined with the sedentary nature of digital device usage and reduced sleep, these conditions can result in obesity which is one of the most challenging public health problems facing many countries around the world (World Health Organisation., 2021b). More than 3 hours of digital technology use per day has been associated with higher body mass index (BMI) standard deviation scores and greater odds of being overweight (Shen et al., 2021). In the UK, Obesity costs the NHS around £6.5 billion a year (DHSC Media Team, 2023). Being overweight or obese can have a serious impact on health such as cardiovascular disease (mainly heart disease and stroke), type 2 diabetes, musculoskeletal disorders, and some cancers (endometrial, breast and colon). These conditions cause premature death and substantial disability (World Health Organisation, 2024).

1.5.3 Mental health disorders

Excessive digital media use by children and adolescents appears as a major factor which may hamper the formation of sound psychophysiological resilience (Lissak, 2018). It has been proven that one of the multiple reasons for more and more individuals being affected by depression and feelings of isolation is their addiction to mobile phones and other digital

gadgets, and their dependency on the opinions of other people on the internet. The prevalence of digital addiction differs globally, varying between 8.9 % in Eastern countries and 4.6 % in Western countries (Pan et al., 2020). Moreover, Fear of Missing Out (FOMO) is exacerbated by continual notifications, which seems to place a significant amount of pressure on people to be online all the time. Individuals mention feeling pressured, overwhelmed, and guilty if they are unable to respond to a text right away and that they face a great deal of anxiety whenever their access to messaging becomes constrained (Nakshine et al., 2022).

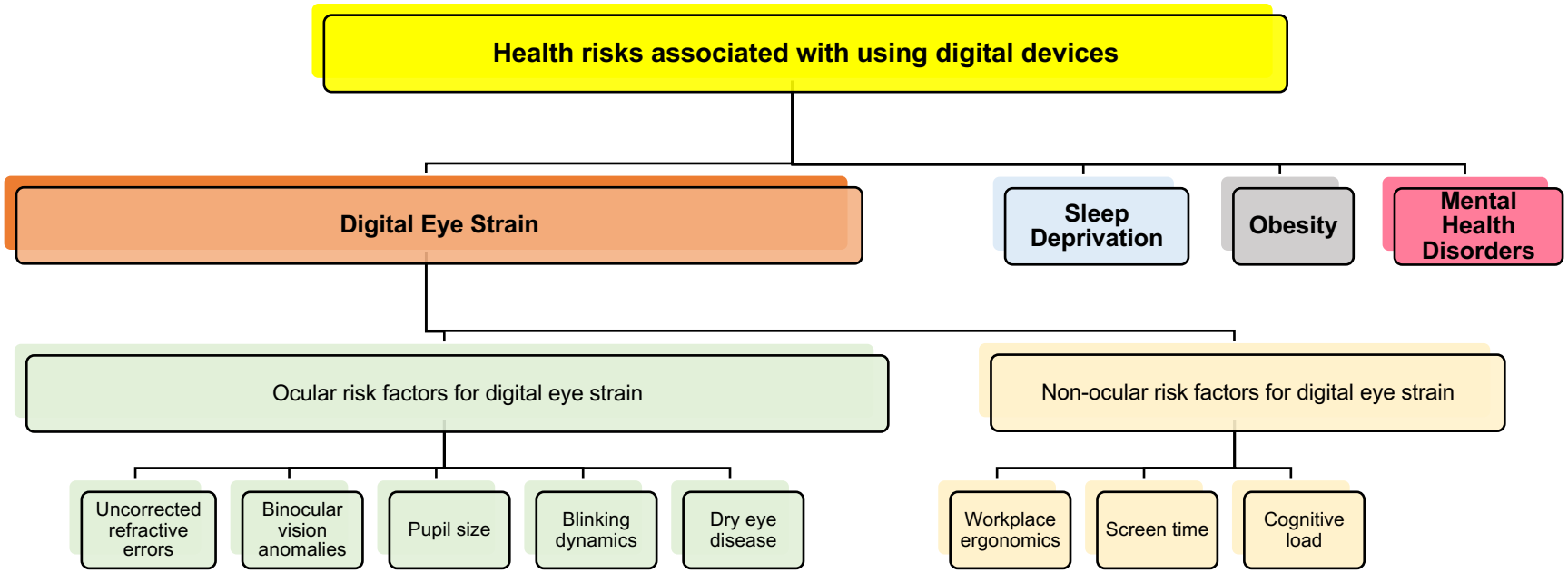


Figure 1.11. A summary of health risks associated with using digital devices.

1.6 Aims of the thesis

DES has been a recognised health problem for over two decades with a prevalence rate of approximately 72 % (Wolffsohn et al., 2023). The literature review has highlighted a need for further investigation into various aspects of DES. The thesis will focus on the following areas.

- Measurement and assessment of DES

Establishing the intraexaminer repeatability and reproducibility of the Bernell pocket CFF tester (Chapter 3), then subsequently utilising this device to determine if CFF can be used as an objective measure of DES (Chapters 4 & 5), evaluating existing questionnaires and commencing the development of a novel DES questionnaire (Chapter 8).

- The potential to improve DES symptoms

Investigating the effect of commercially available privacy screen filters on DES (Chapters 4 & 5) and the association between the symptoms and signs of DES, dry eye disease and convergence insufficiency (Chapter 7).

- The impact cognitive load has on DES, productivity and task accuracy

Tracking visuo-ocular symptoms during prolonged (1-hour) digital tasks and assessing how higher and lower cognitive load levels influence DES symptoms, productivity, and task accuracy (Chapter 6).

By addressing these areas, the research aims to bridge some of the existing gaps in DES research and potentially improve the quality of life for individuals affected by this prevalent condition.

Chapter 2. Instrumentation for the analysis of digital eye strain

2.1 Introduction

The literature review presented in Chapter 1 emphasised the need for further investigation into various aspects of DES. Given that DES has a multifactorial aetiology (Yammouni and Evans, 2021), the experimental chapters of the thesis employ a range of instruments to investigate various aspects of the condition. These include assessments of symptomology, visual acuity, binocular vision, accommodation, pupil size, critical flicker-fusion frequency, as well as the ocular surface and tear film characteristics in individuals with DES. This chapter provides a detailed description of the instruments used in these investigations, alongside a discussion of relevant findings from previously published studies that have employed similar techniques.

2.2 Measuring the symptomology of digital eye strain

Symptoms of DES are varied and include blurred vision, ocular dryness, ocular pain, ocular tiredness, ocular soreness, asthenopia, burning, light sensitivity, headache, and neck / shoulder pain (Portello et al., 2012, Seguí Mdel et al., 2015, Rosenfield, 2016). When assessing symptomology, it is important to identify whether symptoms are specific to digital device usage, ocular surface disease, performing a sustained near-vision task, or a combination of some or all of these variables (Rosenfield, 2011). To assess the symptomology of DES sufferers, four questionnaires have been used in this programme of research. DES symptoms were evaluated using the Computer Vision Syndrome Questionnaire (CVS-Q) (Seguí Mdel et al., 2015) and an adapted version of Hayes *et al*. (2007) questionnaire, dry eye symptoms were evaluated using the Ocular Surface Disease Index (OSDI) questionnaire (Schiffman et al., 2000), and convergence insufficiency symptoms were evaluated using the revised Convergence Insufficiency Symptoms Survey (CISS) questionnaire (Borsting et al., 2003, Rouse et al., 2004).

2.2.1 Computer Vision Syndrome Questionnaire

The Computer Vision Syndrome Questionnaire (CVS-Q; Appendix 1) is the most widely used questionnaire (Table 2.1) that is validated and specifically designed for the diagnosis of DES (Seguí Mdel et al., 2015). The CVS-Q design is based on the results of a literature review evaluating the associations between visual display terminal (VDT) exposure and the occurrence of ocular and visual symptoms (experienced in a week). The CVS-Q was refined using Rasch analysis and includes 16 symptoms associated with DES. Rasch analysis is a

psychometric technique that was developed to improve the precision with which researchers construct instruments, monitor instrument quality, and compute respondents' performances (Boone, 2016). The CVS-Q scores both the frequency (never, occasionally, or often) and severity (moderate or intense) of the symptom, each on a 0-2 scale, and multiplies these together. The total score which can be achieved is 36, where 6 or more is considered diagnostic of the condition (sensitivity 75.0% and specificity 70.2%; Seguí Mdel et al., 2015). The CVS-Q has demonstrated good test-retest repeatability (ICC = 0.802; 95% CI: 0.673, 0.884) for both the scores obtained and DES classification (Seguí Mdel et al., 2015).

Author, year, and country	Participants	Mean age (years)	Prevalence of DES (%)
Tauste *et al*. (2016) Spain	N = 426 Office workers	47.3 ± 8.9	51.0
Artime Ríos *et al*. (2019) Spain	N = 622 Healthcare workers	46.3 ± 10.9	56.9
Boadi-Kusi *et al*. (2020) Ghana	N = 200 University administrative staff	31.0 ± 4.7	51.5
Sánchez-Brau *et al*. (2020) Spain	N = 109 Presbyopic computer terminal operators	54.0 ± 4.8	74.3
Cantó-Sancho *et al*. (2021) Spain	N = 244 University students	20.7 ± 2.1	76.6
Fernandez-Villacorta *et al*. (2021) Peru	N = 106 University graduate students	Not reported	62.3
Gammoh (2021) Jordan	N = 382 University students	21.5 ± 1.8	94.5
Ganne *et al*. (2021) India	N = 941 Adult students of online classes, teachers of online classes, and general population	Not reported	50.6 in students 33.2 in the general public

Mohan *et al*. (2021) India	N = 217 Children	13.0 ± 2.5	50.2
Wang *et al*. (2021) China	N = 137 Medical students	19.6 ± 0.8 18.9 ± 0.8	63.5
Zayed *et al*. (2021) Egypt	N = 108 Information Technology professionals	Not reported	82.4
Li *et al*. (2022) China	N = 2005 School students	12.0 ± 3.0	77.0
Wangsan *et al*. (2022) Thailand	N = 527 Students	20.0 ± 2.2	81.0

Table 2.1. Global prevalence of symptomatic digital eye strain (DES) using the Computer Vision Syndrome Questionnaire (CVS-Q). Adapted from the 'TFOS Lifestyle: Impact of the digital environment on the ocular surface' (Wolffsohn et al., 2023).

2.2.2 Adapted version of Hayes *et al*. (2007) questionnaire

As the CVS-Q does not ask about symptoms experienced in 'real-time', an alternative questionnaire was used when assessing symptoms whilst performing a digital task (Chapter 6). Hayes *et al*. (2007) developed a 21-item questionnaire assessing the effect of computer use on ocular and non-ocular symptoms and quality of life (Hayes et al., 2007). The original questionnaire graded symptoms on a scale from 0 (no symptoms) to 6 (severe symptoms) and was used in two subsequent studies (Chu et al., 2011, Portello et al., 2012). The author of the thesis adapted the original questionnaire and created an 8-item questionnaire (Figure 6.3) which graded symptoms on a scale from 0 (no symptoms) to 10 (very severe symptoms). The work was subsequently published in a peer-reviewed journal (Appendix 8).

2.2.3 Ocular Surface Disease Index Questionnaire

Many of the symptoms that are experienced in DES overlap with symptoms of dry eye disease (DED) such as burning, foreign body sensation, tearing, eye redness, eye pain, and dryness. Therefore, the DED symptomology and the impact of dry eye on vision-related

activities of daily life within the previous week was assessed using the Ocular Surface Disease Index (OSDI) questionnaire (Appendix 2).

The OSDI comprises of 3 subscales: ocular symptoms (3 questions), vision-related functions (6 questions), and environmental triggers (3 questions). Each question is answered on a 5-point scale ranging from 'none of the time' to 'all of the time'. The OSDI total score ranges from 0 to 100 points and is obtained by multiplying the total score of all the questions by 25 and dividing the result by the number of valid answers. The total score can then be used to classify the respondent's dry eye symptoms as normal (0-12 points), mild (13-22 points), moderate (23-32 points), or severe (33-100 points), where ≥ 13 (out of 100) indicates dry eye (sensitivity 60 %, specificity 83 %) (Schiffman et al., 2000, Ozcura et al., 2007, Wolffsohn, 2023). However, the symptom severity is not reported by the patient. The OSDI has good validity, test-retest reliability (ICC = 0.70 - 0.82), and consistency (Schiffman et al., 2000, Grubbs et al., 2014) and has been used in over 620 global research studies (Sánchez-Brau et al., 2023) making it the most frequently used symptomology questionnaire in dry eye research.

2.2.4 The revised Convergence Insufficiency Symptom Survey Questionnaire

Some DES symptoms overlap with symptoms of convergence insufficiency (CI) such as blurred vision, double vision, difficulty focusing for near vision, and headache. CI symptomology was assessed using the revised Convergence Insufficiency Symptom Survey (CISS) questionnaire (Appendix 3).

The revised CISS is a valid and reliable (ICC = 0.885) questionnaire that can be used in both clinical practice and research studies (Rouse et al., 2004). The revised CISS comprises of 15 questions and each question is scored as never (0 points), infrequently (1 point), sometimes (2 points), fairly often (3 points), and always (4 points). The CISS score is determined by summing the points for all 15 questions, which can range from 0 to 60, where ≥ 21 (out of 60) indicates CI (sensitivity 97.8% and specificity 87.0%) (Rouse et al., 2004).

Questionnaire	Population examined	Gold standard test	Sensitivity (%)	Specificity (%)	Intra-class correlation coefficient (ICC)
Computer Vision Syndrome Questionnaire (CVS-Q)	N = 266 VDT workers in a public institution	Not compared against a gold standard test	75.0	70.2	0.80
Ocular Surface Disease Index (OSDI)	N = 109 100 dry eye patients and 9 normal controls	McMonnies Dry Eye Questionnaire National Eye Institute Visual Function Questionnaire - 25	60.0	83.0	0.70 - 0.82
The revised Convergence Insufficiency Symptom Survey (CISS)	N = 92 46 convergence insufficiency patients. 46 normal controls	The Convergence Insufficiency Symptom Survey	97.8	87.0	0.89

Table 2.2. Sensitivity, specificity, and intra-class correlation coefficient values for the Computer Vision Syndrome Questionnaire (CVS-Q), Ocular Surface Disease Index (OSDI) and the revised Convergence Insufficiency Symptom Survey (CISS) as reported by the developing authors.

Questionnaire	Symptom(s) assessed	Time frame over which the symptoms are experienced
Computer Vision Syndrome Questionnaire (CVS-Q)	Visual symptoms related to exposure to computers in the workplace	In a week
Adapted version of Hayes *et al*. (2007) questionnaire	Symptoms whilst performing a digital task	Real-time
Ocular Surface Disease Index (OSDI)	Dry eye disease and its effect on vision	Within the previous week
The revised Convergence Insufficiency Symptom Survey (CISS)	Convergence insufficiency	Not stated, assumed to be real-time

Table 2.3. Table showing each questionnaire used within the thesis, the symptoms assessed by each questionnaire and the time frame over which the symptoms are experienced.

2.3 Objective measurements of digital eye strain

Binocular distance and near visual acuities, near stereoacuity, near fixation disparity, near ocular alignment, subjective binocular accommodative facility at near, subjective break and recovery for the near point of convergence and the critical flicker-fusion frequency were all measured with the participants wearing their appropriate habitual spectacle correction (i.e. distance vision correction for distance tasks and near vision correction for near tasks) under ambient illumination in the same room. Room temperature and humidity were also recorded. The order of the measurements was chosen to minimise the effects of fatigue (Figure 2.1). To stabilise binocular vision, binocular distance and near visual acuities were measured first. Oculomotor function tests can be divided into those that maintain fusion (binocular tests such as near stereoacuity and near fixation disparity), those which dissociate the eyes (near cover test) and those which can stress the visual system (subjective binocular accommodative facility at near, near point of convergence and critical flicker-fusion frequency). As a general principle, binocular tests should always precede dissociation tests and those which can stress the visual system (Franklin, 2008). A rest period of approximately 1-minute was left between the different test procedures and the participants were instructed to rest for 30 seconds by looking at the distance visual acuity chart between repeated measurements (Talens-Estarelles et al., 2022a).

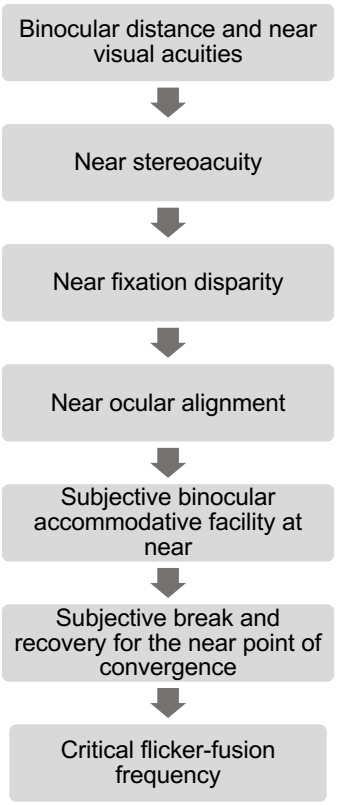


Figure 2.1. Flowchart showing the order of visual function, binocular vision status, ocular alignment, accommodation, convergence, and critical flicker-fusion frequency tests performed.

2.3.1 ETDRS and Bailey-Lovie word reading chart

The ETDRS is a logMAR chart which is used in most major research studies throughout the world (Bailey and Lovie-Kitchin, 2013). LogMAR charts are the gold standard for visual acuity chart design due to the constant 0.10 log unit difference between each successive row on the chart and the ability to score individual letters which provides a more precise measure of visual acuity (Bailey and Lovie-Kitchin, 2013). The Bailey-Lovie word reading chart conforms with the standards established by the ICO and is in accordance with the mathematical backgrounds of EN-ISO 8596 (Radner, 2017). Both, monocular and binocular measurements were taken using a physical chart at the standard chart testing distance of 4 metres for distance vision and at the participants' habitual working distance for near vision.

2.3.2 Original Stereo Fly Stereotest

Near stereoacuity was measured using the Original Stereo Fly Stereotest at the standard viewing distance of 40 cm (Nishikawa et al., 2015). Polarised glasses were worn over the top of the participants' habitual spectacle correction for near vision. The Original Stereo Fly

Stereotest was used due to its good repeatability (COR: ± 12 seconds of arc) and ability to distinguish between different grades of stereopsis, ranging from 800 to 40 seconds of arc (Antona et al., 2015).

2.3.3 Mallett unit

The Mallett unit is commonly used in the UK to detect fixation disparity (Karania and Evans, 2006). The Mallett unit does not quantify fixation disparity, instead, it measures the associated phoria, which is the 'aligning prism' that nullifies the subjective disparity both horizontally and vertically (Conway et al., 2012). The test was performed with a polarised visor placed over the top of the participants' habitual spectacle correction for near vision. If only one nonius strip was seen, suppression was present, and the test was stopped. Although it is a subjective test, the Mallett unit has shown good repeatability (-0.007 (-0.14 to 0.13 95% CI)) (Alhassan et al., 2015) and is more reliable than the Sheedy unit, which tends to give a larger spread of fixation disparity measurements (Dowley, 1989, Alhassan et al., 2015).

2.3.4 Near cover test

Near ocular alignment was assessed using the single cover test, cover / uncover test, and the alternating cover test. The single cover test is used to determine if a heterotropia is present, the cover / uncover test is used to determine if a heterophoria is present when binocular fusion is suspended, and the alternating cover test suspends binocular fusion allowing the full deviation to be measured. The fixation target, which corresponded to N5 near acuity, was viewed at the participants' habitual near working distance. The amount of movement observed was then estimated by the author of the thesis. Rainey *et al*. (1998) found that when used by experienced clinicians, each cover test technique appears to be a reliable method of heterophoria determination (Rainey et al., 1998). The author of the thesis is a qualified UK Optometrist and has been registered with the General Optical Council since 2018.

2.3.5 Near subjective binocular accommodative facility

Accommodative facility measures the ability of the crystalline lens to alter accommodation rapidly and accurately and has been assessed in several studies investigating DES (Sheedy and Parsons, 1990, Pandian et al., 2006, Rosenfield et al., 2009, Golebiowski et al., 2018,

Talens-Estarelles et al., 2022a). Participants viewed a target, which corresponded to N5 near acuity, at a 40 cm working distance. ± 2.00 DS manual flip lenses were presented binocularly, and the participants were asked to report when the target was clear as + 2.00 DS and – 2.00 DS lenses were alternately presented. Once the participant reported the letters were clear, the lenses were flipped. Accommodative facility was measured as the number of cycles of plus and minus lenses the participants were able to clear in 1 minute (cpm), where 1 cycle was clearing 1 set of plus and minus lenses.

2.3.6 Near point of convergence

The subjective break and recovery for the near point of convergence (NPC) was measured using a traditional RAF rule as the measurements obtained are highly reproducible (Parkinson et al., 2001) and the induced relative proximal accommodation and convergence are clinically insignificant (Hung et al., 1996). The RAF rule was held in the depressed position of 45 degrees and the cheek rest was placed on the participant's inferior orbital margin. The patient focussed on the black dot and the target was moved towards the participant's eyes at a constant rate of about 1 to 2 cm per second (Siderov et al., 2001). The subjective break point was when the participant either reported diplopia or when the slider was stopped by the cheek rest. The slider was then moved back, away from the participant's eyes, and the recovery was noted when the participant reported that they were no longer experiencing diplopia. The objective values of break and recovery were noted when the examiner observed that one or both eyes diverged from fixation, and when both eyes regained convergence on the target, respectively. All readings were measured to the nearest 0.5 cm (Sharma, 2017). Due to the higher variability of data, the subjective break and recovery was measured 3 times and an average value for each measurement was obtained.

2.3.7 Critical flicker-fusion frequency

The critical flicker-fusion frequency (CFF) is the lowest frequency at which a flickering light is perceived as continuous. It is assumed that the CFF can reflect the basic temporal function of the visual system and is therefore a good measure of its performance (Eisen-Enosh et al., 2017). As CFF is a recognised measure of fatigue and mental workload (Thackray, 1985, Luczak and Sobolewski, 2005), it would not be unreasonable to suggest that changes in flicker-fusion values could be used as an objective measure of DES. The ability to detect flicker-fusion is dependent on several internal and external factors, and may also be

influenced by task time (Chi and Lin, 1998). Internal factors include age, sex, personality traits, circadian variation in brain activity, fatigue, and cognitive functions such as visual integration, visuomotor skills, and decision-making processes (Umeton et al., 2017, Balestra et al., 2018). External factors include the frequency and amplitude of the modulation, the luminance, colour, viewing distance and size of the stimulus, and the retinal location (Shams et al., 2002).

The 'Handy Flicker HF-II (Neitz Instrument, Tokyo, Japan)' has been commonly used to measure CFF (Ide et al., 2015, Lin et al., 2017, Satou et al., 2017, Yamashita et al., 2019, Munsamy et al., 2022a) but at the time of writing the HF-II was not widely available. An alternative, the Bernell pocket CFF tester device which has been used in two previously published studies (Tannen et al., 2015, Benassi et al., 2021), was used instead (Chapter 3).

2.3.8 Ocular surface and tear film

The Oculus Keratograph 5M topographer (K5M; Oculus Optikgerate, Wetzlar, Germany) was used to examine the ocular surface and tear film as it is quick, non-invasive, and reliable (Wei et al., 2016). The K5M represents the gold standard for ocular surface investigation and evaluation of ocular surface diseases (Tian et al., 2016, García-Marqués et al., 2021). The K5M has been shown to have a far superior discriminative ability of detecting dry eye compared to that of subjective assessments (Wang and Craig, 2018) and it has good repeatability and reproducibility for all measurements (ICC ≥ 0.75) (Tian et al., 2016). The testing procedures were based on the guidelines of the TFOS DEWS II Diagnostic Methodology report (Wolffsohn et al., 2017) and were performed in the following (least invasive to most invasive) order - spontaneous blinking pattern, tear meniscus height (TMH), limbal and bulbar redness, lipid layer thickness (LLT), non-invasive breakup time (NIKBUT), corneal and conjunctival staining, lid wiper epitheliopathy (LWE) and upper and lower eyelid meibography. Slit lamp biomicroscopy was used to evaluate meibomian gland function (Figure 2.2).

The TFOS DEWS II global report defines dry eye as "..a multifactorial disease of the ocular surface characterised by a loss of homeostasis of the tear film, and accompanied by ocular symptoms, in which tear film instability and hyperosmolarity, ocular surface inflammation and damage, and neurosensory abnormalities play etiological roles" (TFOS, 2017). To manage dry eye disease (DED) appropriately, a diagnosis and subtype classification must be made so that the most effective treatment can be provided. DED can also be diagnosed if there is a sufficient symptomology score, and if any of the 3 homeostasis markers (non-invasive

breakup time, osmolarity, and ocular surface staining with sodium fluorescein and lissamine green) are positive.

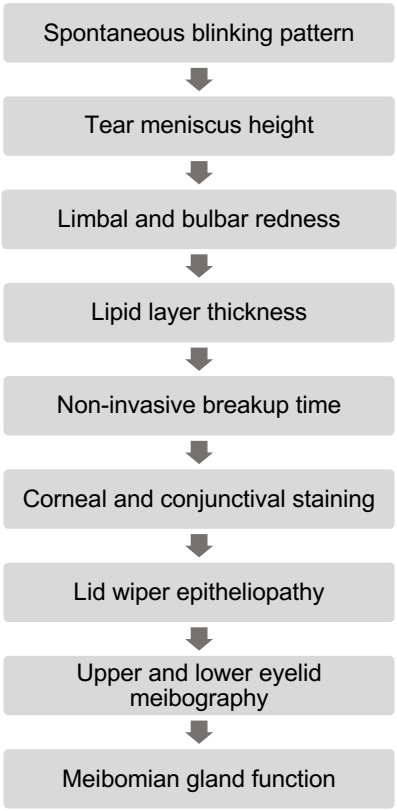


Figure 2.2. Flowchart showing the order of ocular surface and tear film tests performed.

To subclassify aqueous-deficient dry eye, the K5M was used to quantify the tear meniscus height (TMH). The tear meniscus contains between 75 % to 90 % of the tears (Holly, 1985) and the tear meniscus height (TMH) can be used as an indicator of the total tear volume (Yokoi et al., 1999, Palakuru et al., 2007). A normal TMH is ≥ 0.20mm (Wolffsohn et al., 2017). In each participant, 3 TMH images were captured and measured perpendicular to the inferior lid margin (temporally, centrally, and nasally) using an integrated ruler (Figure 2.3).

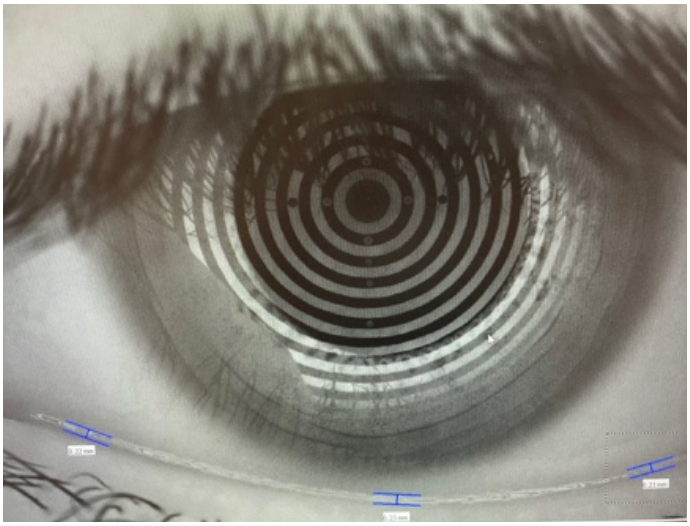


Figure 2.3. Tear meniscus height (TMH) images were captured using the Oculus Keratograph 5M and were measured perpendicular to the inferior lid margin (temporally, centrally, and nasally) using an integrated ruler.

To subclassify evaporative dry eye, the K5M was used to evaluate limbal and bulbar conjunctival redness, spontaneous blinking pattern, lipid layer thickness, non-invasive breakup time, corneal and conjunctival staining, lid wiper epitheliopathy, and upper and lower eyelid meibography. The most common clinical sign suggestive of ocular surface inflammation is ocular redness (Amparo et al., 2013). The K5M uses a Placido ring system which scans the exposed limbal and bulbar conjunctiva (Figure 2.4). It immediately generates an image of 1156 x 873 pixels and a redness score on the computer screen (Pérez-Bartolomé et al., 2018). The degree of redness is based on the JENVIS grading scale and is in 0.1 increments (grades 0 to 4 where 0 = no findings and 4 = severe diffuse injections).

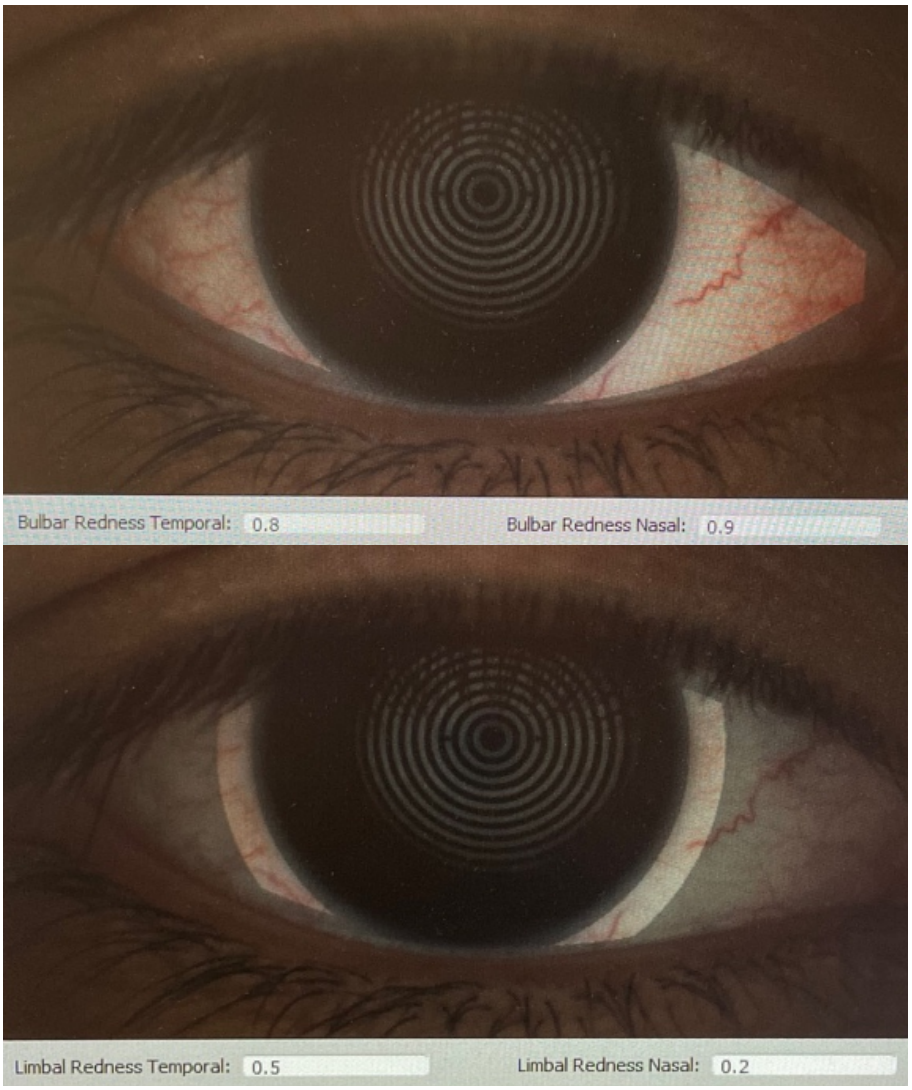


Figure 2.4. Bulbar and limbal redness images were captured using the Oculus Keratograph 5M and were graded using the integrated JENVIS grading scale in 0.1 increments.

The K5M has an in-built video camera function which was used to record the blink rate and completeness of blinks over a 30-second period. The video was then stopped and replayed, and the number of blinks, and the number of complete blinks (when the upper lid meets and overlaps the lower lid) were counted manually (Jiang et al., 2013) by the same examiner i.e. the author of the thesis.

The lipid-layer thickness (LLT) was recorded for 20 seconds using the K5M and assessed through the lipid layer interference pattern. The Guillon grading scale was used (Guillon, 1998), where the lipid layer interference pattern is classified as 1 = open meshwork (13-15 nm), 2 = closed meshwork (30-50 nm), 3 = wave (50-80 nm), 4 = amorphous (80-90 nm), or

5 / 6 / 7 = normal / abnormal / globular coloured fringes (90-140 nm) (Tomlinson et al., 2011, García-Marqués et al., 2022).

The K5M was used to measure the non-invasive (keratography) breakup time (NIKBUT); this is a measure of the time between a blink and the disruption of the Placido rings reflected in the tear film. NIKBUT was measured 3 times and an average value was obtained (Tian et al., 2016). The average NIKBUT value was then used during data analysis. The K5M illumination system consists of 200 red LEDs (wavelength 653 nm). An illuminated ring pattern, consisting of 22 rings, is projected onto the cornea in the form of Placido rings. Once the participant is correctly aligned, the software prompts the practitioner to ask the participant to blink twice. The second blink triggers the video recording and measurement. The recording and measurement stop when either the participant blinks or significant distortion of the reflected image of the Placido rings occurs. The computer displays a video of the reflected mires, an image with the detected mire distortion overlaid and a corneal map with the time of the first detected tear film breakup detected at each location colour coded. The time to first breakup and total measuring time is also recorded to 1/100th of a second (Best et al., 2012).

A mixture of 2 % sodium fluorescein and 1 % lissamine green provides very good simultaneous corneal and bulbar conjunctival staining (Korb et al., 2008). 2 separate ophthalmic strips, impregnated with 1.0 mg of sodium fluorescein and 1.5 mg of lissamine green respectively, were wetted with a single drop (10-20 μl) of saline (McGinnigle et al., 2012) and applied sequentially to the inferior fornix of both eyes. The fluorescein strip was shaken to minimise the installation whereas the drop of lissamine green was maintained on the strip for at least 5 seconds to increase the concentration and the whole drop instilled onto the peripheral ocular surface as recommended (Wolffsohn et al., 2017). Participants were told to blink several times to ensure adequate mixing of the dyes and to allow for the stain to distribute evenly across the ocular surface. Through the use of blue light and a built-in yellow filter, the K5M captured any corneal and conjunctival staining. The severity of staining was measured by the Oxford grading scale (grades 0, 0.5, 1, 2, 3, 4, 5 where 0 = no staining and 5 = severe staining, see Appendix 4). Lower lid wiper epitheliopathy (LWE) was assessed by everting the lower eyelid with a cotton bud. The LWE was measured by using the grading protocol proposed by Korb (Appendix 5); grades 0, 0.5 to 1, 1.5 to 2 & 2.5 to 3, where 0 = no LWE and 2.5 to 3 = grade 3 LWE which means the horizontal length of staining > 10 mm and the saggital height of staining > 75 % (Korb et al., 2010).

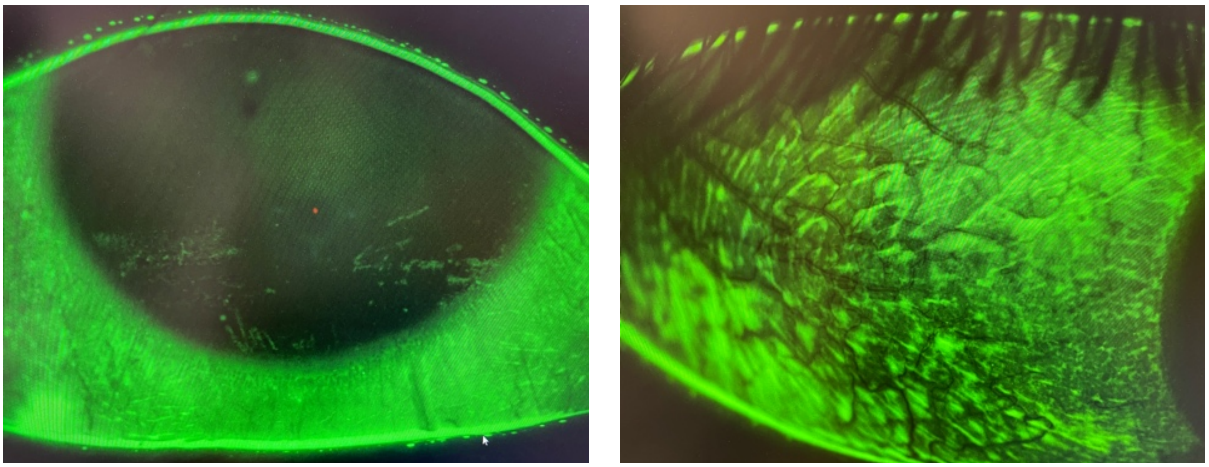


Figure 2.5. The Oculus Keratograph 5M was used to capture corneal and conjunctival staining which was then subjectively graded through the by the Oxford grading scale. In the above images, corneal staining = grade 2 and conjunctival staining = grade 1.

Following eversion of the upper and lower eyelids by a cotton-tipped applicator, the K5M was used to provide an in vivo visualisation of the meibomian gland morphology via infrared light. The meibomian glands are a type of sebaceous gland that line the upper and lower eyelids in a single row and secrete lipids onto the tear film. There are approximately 30-40 glands in the upper eyelid and 20-30 glands in the lower eyelid (Utheim et al., 2014). The placement of the 840 nm infra-red (Diz-Arias et al., 2023) diodes in the K5M have been adjusted to minimise reflections from the lid (Wong et al., 2019). Several features can be assessed including meibomian gland dropout, shortening, dilation, and tortuosity. Normal meibomian glands appear as hyper-illuminated regions with no gland shortening or dropout. (Craig and Wang, 2023). The Pult 5-grade meiboscale (Appendix 6) was used to evaluate the condition of the meibomian glands (degrees 0-4, where degree 0 = normal, no gland dropout / no atrophy and degree 4 = severe, > 75 % gland dropout / atrophy (Pult and Riede-Pult, 2013).

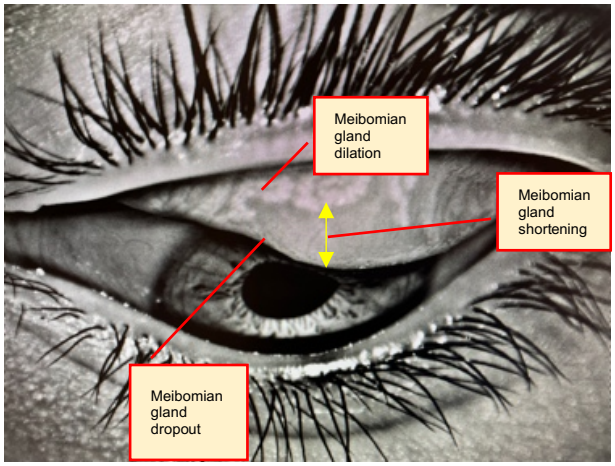


Figure 2.6. The Oculus Keratograph 5M was used to image the meibomian glands. In the above image, meibomian gland dropout, shortening, and dilation are all present. The upper lid was graded as degree 3 on the Pult 5-degree scale.

Slit lamp biomicroscopy was used to evaluate meibomian gland function. The ducts, meibum quantity, quality, and expressibility were all assessed. The Korb Meibomian Gland Evaluator (by Tear Science) is a small handheld device that when applied for 10-15 seconds (Korb and Blackie, 2008) provides a repeatable standardised force of 1.25g/mm^2 along the lower lid margin over an area of approximately 40 mm^2 (Tomlinson et al., 2011, Brujic, 2017). The Korb Meibomian Gland Evaluator achieves simultaneous expression from approximately 8 meibomian glands. Gland expressibility is scored according to the number of the 8 glands from which a fluid secretion can be expressed (Tomlinson et al., 2011). Scores of 0, 1, and 2 indicates that ≥ 5 glands, 3−4 glands, and 1−2 glands are expressible. A score of 3 indicates that no gland is expressible. The meibum quality of each gland was scored from 0 to 3 where 0 = clear liquid secretion; 1 = cloudy liquid secretion; 2 = cloudy particulate fluid; 3 = inspissated, similar to toothpaste (Wang et al., 2018a). Normal meibum quality of each gland should form an oil-dome with a clear liquid secretion upon expression (Korb and Blackie, 2008, Blackie and Korb, 2009).

Figure 2.7. The Korb Meibomian Gland Evaluator (by Tear Science).

2.3.9 Dynamic refraction and pupil size

The Grand Seiko Auto Refractor / Keratometer WAM-5500 (Grand Seiko Co. Ltd., Hiroshima, Japan) is a reliable and valid binocular open-field autorefractor and keratometer (Sheppard and Davies, 2010). When connected to an external laptop via an RS-232 port, the WAM-5500 can record dynamic refraction and pupil size. For pupil diameters ≥ 2.3 mm, the WAM-5500 can measure refraction in the range of ± 22 D sphere and ± 10 D cylinder, in increments of 0.01, 0.12 or 0.25 D for power and 1° for cylinder axis (Sheppard and Davies, 2010). In dynamic (high-speed) mode, the mean spherical equivalent (MSE) refractive error and pupil diameter can be recorded at a rate of 5 Hz by interfacing with a laptop running the WAM communication system (WCS-1) software, allowing the objective measurement of a participant's dynamic accommodative response to a target over a desired time frame. The software records dynamic results, including time (in seconds) of each reading, MSE refraction and pupil size, in the form of an Excel Comma Separated Values (CSV) file (Sheppard and Davies, 2010). In this programme of research, the dynamic accommodative response and pupil size was measured over a 20-second period, with the participant performing a high-cognitive load task on a laptop whilst looking through the WAM-5500 at a 50 cm working distance.

Figure 2.8. The set-up whilst measuring the dynamic refraction and pupil size with the Grand Seiko Auto Refractor / Keratometer WAM-5500 (Grand Seiko Co. Ltd., Hiroshima, Japan).

Chapter 3. Repeatability and reproducibility of the Bernell pocket critical flicker-fusion frequency tester

Abstract

Purpose. To determine the intraexaminer repeatability and reproducibility of critical flicker-fusion frequency (CFF) measurements obtained with the Bernell pocket CFF tester.
Methods. 49 participants (30 female) with an average age of 29.9 ± 11.0 years and healthy eyes were recruited in this prospective, repeated measures study. In all participants, 3 consecutive measurements using the Bernell pocket CFF tester were taken on 3 separate visits. The intraexaminer repeatability and reproducibility of measurements were assessed by Cronbach's alpha (α), the Intraclass Correlation Coefficient (ICC), the Coefficient of Repeatability (CR), and the Coefficient of Variation (CV).
Results. The range of CFF measurements obtained was between 42 Hz and 53 Hz. The repeatability and reproducibility of the CFF measurements were good (α = 0.97, ICC = 0.97, CR = 1.55 and CV = 4%).
Conclusion. CFF measurements obtained with the Bernell pocket CFF tester provide high intraexaminer repeatability and reproducibility.

3.1 Introduction

The critical flicker-fusion frequency (CFF) is the lowest frequency at which a flickering light is perceived as continuous. It is assumed that the CFF can reflect the basic temporal function of the visual system and is therefore a good measure of its performance (Eisen-Enosh et al., 2017). P pathway (chromatic) flicker-fusion thresholds are between the range of 10 to 15 Hz, whereas M pathway (achromatic) flicker-fusion thresholds are between 35 to 60 Hz (Mewborn et al., 2015, Brown et al., 2018). For many years it was believed that the human eye could only detect flicker up to 90 Hz, however, Davis *et al*. (2015) found that humans can perceive visual flicker artifacts at rates over 500 Hz when a display includes high frequency spatial edges (Davis et al., 2015).

The ability to detect flicker-fusion is dependent on several internal and external factors, and may also be influenced by task time (Chi and Lin, 1998). Internal factors include age, sex, personality traits, circadian variation in brain activity, fatigue, and cognitive functions such as visual integration, visuomotor skills, and decision-making processes (Umeton et al., 2017, Balestra et al., 2018). External factors include the frequency and amplitude of the modulation, the luminance, colour, viewing distance and size of the stimulus, and the retinal location (Shams et al., 2002).

Currently, there are no widely accepted objective measures of digital eye strain (DES; (Wolffsohn et al., 2023)). As CFF is a recognised measure of fatigue and mental workload (Thackray, 1985, Luczak and Sobolewski, 2005), it would not be unreasonable to suggest that changes in flicker-fusion values could be used as an objective measure of DES. However, research within this area of study has produced varying results (Table 3.1).

Iwasaki *et al*. (1989) researched the change in chromatic CFF values during repetitive tasks with cathode ray tube monitors. Red CFF values decreased significantly 15 minutes after the start of the task, and green and yellow values decreased significantly 30 minutes after the start of the task (Iwasaki et al., 1989). As this study used older display screen technology, the findings may be less relevant nowadays. More recently, a study involving 160 participants found no change in the chromatic CFF values 30 minutes after continuous smartphone use (Gautam, 2020). Chi and Lin (1998) found that extending the same visual display task time from 20 minutes to 60 minutes increased the CFF sensitivity amongst their 10 participants (Chi and Lin, 1998). Yan and Rosenfield (2022) measured the CFF values in 30 young participants before and after a 20-minute reading task, which was performed on a tablet computer and a printed book. After performing the task in both conditions, no significant change in the CFF values were observed. When considering the digital condition only, no significant correlation was observed between the changes in CFF and reported symptoms. The results led the authors to conclude that changes in the CFF cannot be used as an objective measure of DES (Yan and Rosenfield, 2022). However, as this study used a 20-minute task as opposed to Chi and Lin's (1998) 60-minute task, it poses the question 'would the results have been any different with a longer and / or more demanding task?'. It is known that individuals use digital devices for many hours per day, therefore it is reasonable to suggest that a 20-minute task is not reflective of modern usage patterns. However more recently, Singh *et al*. (2023) examined the correlation between the change in CFF and subjective reports of visual fatigue in a group of symptomatic computer users and did not find a significant correlation between overall symptom scores and CFF (Singh et al., 2023).

As mentioned in Chapter 2, the 'Handy Flicker HF-II (Neitz Instrument, Tokyo, Japan)' has been commonly used to measure CFF (Ide et al., 2015, Lin et al., 2017, Satou et al., 2017, Yamashita et al., 2019, Munsamy et al., 2022a) but at the time of writing the HF-II was not widely available. An alternative, the Bernell pocket CFF tester device which has been used in two previously published studies (Tannen et al., 2015, Benassi et al., 2021), has not been validated so this was the aim of the reported study.

Figure 3.1. Front and back images of the Bernell pocket CFF tester (Bernell Corporation, Mishawaka, USA). On the display screen, 60 NSTS refers to 60 Hz non-seeing to seeing, 35 STNS refers to 35 Hz seeing to non-seeing and 47.5 Avg refers to the average CFF value which is 47.5 Hz.

Repeatability is the variation in repeat measurements made on the same participant under identical conditions; the smaller the variation, the more reliable the results (Vaz et al., 2013). Test-retest reliability is a method of estimating an instrument's reliability (in this case the instrument is the Bernell pocket CFF tester) by administering it to the same participant or a group of participants, in the same way, on two or more different occasions, over a short period of time (hours or days apart). Good test-retest reliability signifies the internal validity of an instrument and ensures that the measurements obtained in one sitting are both representative and stable over time (Hobbs, 2023). There are two necessary assumptions in test-retest reliability. The first is that the true score does not change between administrations. The second is that the time period between administration is long enough to prevent learning, carry-over effects, or recall (Vaz et al., 2013).

Author and year	Participants completing the study	Mean age (years)	Measures	Task duration	Findings
Lin *et al*. (2008)	N = 10	20.4	2 experiments. 1. Tracking a scanning line at two different speeds and responding to a designated target presented singly at two different temporal frequencies. 2. Tracking a target with changing screen type and viewing distance. Reaction time, visual acuity (VA), critical flicker-fusion frequency (CFF) and accommodative power were measured before and after the task.	20- or 60-minutes.	Reaction time, VA, accommodative power, and CFF all decreased by extending the task time from 20- to 60 minutes.
Kang *et al*. (2009)	N = 20	17.5 ± 0.6	Participants were asked to read an E-book and a conventional book respectively. CFF, reading speed, reading accuracy and a visual fatigue measure were all taken.	40- to 60-minutes.	CFF significantly reduced in the E-book condition indicating higher eye fatigue compared to the conventional book condition.

Maeda *et al*. (2011)	N = 7	35.0	CFF, visual fatigue and a sleep questionnaire were measured before and after the task.	4-hours.	CFF declined after reading and after reduced sleep. Visual fatigue increased after reading and after reduced sleep.
Benedetto *et al*. (2013)	N = 12	27.0 ± 4.0	3 different devices were used. 1. Paper book 2. Kindle Paperwhite 3. Kindle Fire HD Subjective visual fatigue scale and CFF were measured before and after the task.	70-minutes.	The results do not support the hypothesis that task-induced changes in CFF can be used as a correlate for digital eye strain (DES) symptom scores.
Ide *et al*. (2015)	Control lenses N = 11 Low blue-blocking lenses N = 11 High blue-blocking lenses N = 11	34.6 ± 3.3 33.4 ± 2.2 31.4 ± 2.0	Participants who used high (53.9 %) and low (26.1 %) blue blocking lenses were exposed to an LED-LCD computer display for 2 hours.	2-hours.	CFF was more negatively affected with greater blue light exposure. Answers to the questionnaire were unaffected by the type of lens used.

Lin *et al*. (2017)	Clear lenses N = 12 Low blue-blocking lenses N = 12 High blue-blocking lenses N = 12	23.3 ± 0.8 24.6 ± 1.4 25.0 ± 2.7	3 spectacle lens conditions while performing a 2-hour computer task. 1. Clear lenses 2. Low blue-blocking lenses 3. High blue-blocking lenses. CFF and a 15-item questionnaire were measured before and after computer use.	2-hours.	An increase in CFF was seen in the high blue-blocking lenses but no significant change in CFF was seen in the low blue-blocking lenses or clear lenses immediately after the task. Less ocular symptoms were reported in the high blue-blocking lenses condition.
Gautum (2020)	N = 160	18 to 24	A series of green and red-light stimuli at different frequencies adjusted from 20-120 Hz. CFF was measured.	30-minutes.	No change in the chromatic CFF values 30-minutes after continuous smartphone use were seen.
Yan and Rosenfield (2022)	N = 30	24.6 ± 1.3	Reading task (reading random words from a tablet computer or a story from a printed children's book) performed on different days. CFF was measured before and after each of the reading tasks. DES was assessed by a questionnaire.	20-minutes.	No significant correlation was observed between the changes in CFF and reported symptoms.

Singh *et al*. (2023)	N = 120	18 to 40	CFF and visual fatigue symptoms were measured before and after a visually demanding 2-hour computer task.	2-hours.	Visual fatigue symptom scores altered significantly post-task but CFF did not. It was deemed that CFF is not a useful surrogate for symptoms of visual fatigue.

Table 3.1. Table showing studies which have investigated whether critical flicker-fusion can be used as an objective measure of digital eye strain.

3.2 Materials and methods

3.2.1 Participants

The research conducted within Aston University's Vision Science building adhered to the tenets of the Declaration of Helsinki of 1975 and was approved by Aston University's Health and Life Sciences Research Ethics Committee (reference numbers 15/SS/0113 and HLS1822). Participants were recruited from both Aston University and the general public and were enrolled following explanation of the study and after providing written consent.

Participants were included in the study if they were aged 18 years or older. Excluded individuals were those with epilepsy and / or any individual who has previously suffered a seizure, pregnant women, and those who had any new or unstable general health conditions and / or medications and / or eye disease. A total of 49 participants were recruited. 30 were female and the average age was 29.9 ± 11.0 years. Their spherical equivalent (SE) prescriptions ranged from +3.00 D to -9.25 D (average -1.79 ± 2.89 D).

3.2.2 Examination protocol

The research study was a prospective, repeated measures study where each participant served as their own control. The study comprised of 3 visits completed on separate days over a period of 3 weeks and each participant attended their visits at approximately the same time (mean time difference between visits = 1.1 ± 1.9 hours). Assessments were conducted in the same room (same room luminance), with the same operator, room temperature of 20.9 ± 1.2 °C and relative humidity of 39.1 ± 8.4 %.

3.2.3 Measurement of critical flicker-fusion frequency

Several methods can be used to measure the CFF; these include the method of constant stimuli (MCS), the staircase method (SM), the method of adjustment and the method of limits (MOL) (Eisen-Enosh et al., 2017). The Bernell pocket CFF tester employs the method of limits to measure CFF (Benassi et al., 2021); the stimulus (flicker) is presented at a high level and is gradually decreased until the participant can no longer perceive it (referred to as seeing to non-seeing or STNS). The stimulus (flicker) is then gradually increased until it is perceivable by the participant (referred to as non-seeing to seeing or NSTS). An average threshold value is then calculated by the device and displayed on the device's screen

(Figure 3.1). To minimise learning effects, the participants were inexperienced and did not have any practice sessions prior to the first visit. The procedure to measure CFF was as follows.

1. Room lights on, participants wore their habitual near vision correction throughout and the test was performed binocularly.
2. Participants were given clear instructions – to look at the circular screen on the Bernell pocket CFF tester and to first report when they could no longer see the flicker (by saying, "the flicker has stopped") and to first report when they could see the flicker (by saying, "it is flickering").
3. The Bernell pocket CFF tester was held at 40 cm (as per the instruction manual; this distance was measured by a metre ruler) directly in front of the participant in primary gaze; at this distance the pocket CFF tester subtends a visual angle of 5.7° (Benassi et al., 2021).
4. The seeing to non-seeing (STNS) button on the tester was held down until the participant verbalised that they could no longer see the flicker. The button was then released.
5. The NSTS button was held down until the participant verbalised that they could see the flicker. The button was then released.
6. The average of the STNS and NSTS values was recorded. Three consecutive CFF measurements were taken and the average CFF threshold value was calculated from the 3 measurements (Ide et al., 2015).

3.3 Statistical analysis

Sample size calculations for reliability studies are typically based on the Intraclass Correlation Coefficient (ICC) (Mokkink et al., 2022). An ICC value greater than 0.8 indicates very good reliability (Koo and Li, 2016). The study wanted to demonstrate that the ICC was at least 0.8 with 80 % statistical power and 5 % significance level ($\alpha = 0.05$). It was suspected that the true ICC was 0.9. A minimum sample size of 41 participants was suggested by the online sample size calculator (Borg et al., 2022) which implements the Walter *et al*. (1998) formula (Walter et al., 1998).

The data were analysed with SPSS (Version 25, SPSS Inc, Chicago, II, USA). Cronbach's alpha (α), the Intraclass Correlation Coefficient (ICC), the Coefficient of Repeatability (CR) and the Coefficient of Variation (CV) were all used to calculate test-retest reliability estimates (Lexell and Downham, 2005).

3.4 Results

The Bernell pocket CFF tester can measure CFF thresholds between 35 Hz and 60 Hz (with a step size of 1 Hz). The range of CFF measurements obtained in the study was between 42 Hz and 53 Hz so no ceiling or floor effect occurred.

Cronbach's alpha (α) is used to estimate the internal consistency or reliability of an instrument. An α value greater than 0.8 indicates a very good level of reliability (Taber, 2018). As shown in tables 3.2, 3.3 and 3.4, the α value was 0.98, 0.95 and 0.97 after the first, second and third visit respectively.

The Intraclass Correlation Coefficient (ICC) assesses how closely variables are related to each other. An ICC value greater than 0.8 indicates very good reliability (Koo and Li, 2016). As shown in tables 3.2, 3.3 and 3.4, the ICC value was 0.98, 0.95 and 0.97 after the first, second and third visit respectively; this means that after the third visit, only 3 % of the observed score variation represented error.

The Coefficient of Repeatability (CR) accounts for both random and systematic error and was calculated by multiplying the Standard Error of the Mean (SEM) by 2.77 (Vaz et al., 2013). The CR of an instrument is directly related to the 95 % limits of agreement proposed by Bland and Altman. The Bland-Altman method calculates the mean difference between two methods of measurement (the 'bias'), and 95 % limits of agreement as the mean difference (1.96 x SD) (Myles and Cui, 2007). The CR is the value below which the absolute differences between two measurements would lie with 0.95 probability (Vaz et al., 2013). As shown in tables 3.2, 3.3 and 3.4, the CR value was 1.58 and 1.55 after the first, second and third visit respectively; considering the CR value after the third visit, a practitioner would need to see a change of at least 1.55 Hz at re-assessment to be 95 % confident that a participant has had a change in their CFF value. A change of less than 1.55 Hz may be due to the inherent mechanical inaccuracy of the Bernell pocket CFF tester.

The Coefficient of Variation (CV) is the ratio of the standard deviation to the mean. The lower the CV value, the more precise the estimate. A CV less than 10 % is very good (Shechtman, 2013). As shown in tables 3.2, 3.3 and 3.4, the CV value was 4 % (0.040) after the first, second and third visit.

	Visit 1	**Reliability measures**				
Number of participants (N)	Mean CFF value	α	ICC	SEM	CR	CV
49	47.84 ± 2.04	0.98	0.98	0.57	1.58	0.040

Table 3.2. Table showing the reliability measures for the Bernell pocket CFF tester after 1 visit (where α = Cronbach's alpha, ICC = Intraclass Correlation Coefficient, SEM = standard error of the mean, CR = Coefficient of Repeatability and CV = Coefficient of Variation.

	Visit 1	**Visit 2**	**Reliability measures**				
Number of participants (N)	Mean CFF value		α	ICC	SEM	CR	CV
49	47.84 ± 2.04	47.79 ± 1.79	0.95	0.95	0.57	1.58	0.040

Table 3.3. Table showing the reliability measures for the Bernell pocket CFF tester after 2 visits (where α = Cronbach's alpha, ICC = Intraclass Correlation Coefficient, SEM = standard error of the mean, CR = Coefficient of Repeatability and CV = Coefficient of Variation.

	Visit 1	**Visit 2**	**Visit 3**	**Reliability measures**				
Number of participants (N)	Mean CFF value			α	ICC	SEM	CR	CV
49	47.84 ± 2.04	47.79 ± 1.79	47.89 ± 1.91	0.97	0.97	0.56	1.55	0.040

Table 3.4. Table showing the reliability measures for the Bernell pocket CFF tester after 3 visits (where α = Cronbach's alpha, ICC = Intraclass Correlation Coefficient, SEM = standard error of the mean, CR = Coefficient of Repeatability and CV = Coefficient of Variation.

3.5 Discussion

The CFF is the lowest frequency at which a flickering light is perceived as continuous and is a recognised measure of fatigue and mental workload (Thackray, 1985, Luczak and Sobolewski, 2005). Currently, there are no widely accepted objective measures of DES therefore it would not be unreasonable to suggest that changes in flicker-fusion values could be used as an objective measure of DES. In the current study, CFF was measured using the Bernell pocket CFF tester. This appears to be the first study to investigate the intraexaminer repeatability and reproducibility of the Bernell pocket CFF tester, despite it being used in

previously published studies (Tannen et al., 2015, Benassi et al., 2021). The results of this study reveal good intraexaminer repeatability and reproducibility of CFF measurements implying that practitioners can confidently use the Bernell pocket CFF tester in future studies.

The Handy Flicker HF-II (Neitz Instrument, Tokyo, Japan) has been used to measure CFF in previous studies (Ide et al., 2015, Lin et al., 2017, Satou et al., 2017, Yamashita et al., 2019, Munsamy et al., 2022a), but to the best of our knowledge its reliability remains unknown. The HF-II has three-colour (red, green and blue) visual targets which can test for eye fatigue (CFF) and optic nerve disease whereas the Bernell pocket CFF tester only uses white-black flicker. Another advantage of the HF-II is that it can measure a larger range of CFF thresholds, between 1 Hz and 79 Hz with a step size of 1 Hz (Lin et al., 2017) compared to the Bernell pocket CFF tester which can only measure CFF thresholds between 35 Hz and 60 Hz, with a step size of 1 Hz. However, all of the participants assessed in this study had a CFF within the Bernell pocket CFF tester's range so no ceiling or floor effects occurred.

It has been well-documented that CFF thresholds reduce with increasing age (Mewborn et al., 2015). Kaur *et al*. (2020) measured the mean CFF threshold amongst adults aged between 18 and 45 years of age. The results showed that the highest CFF threshold was observed within the 18-21 years age group (50.0 Hz) and the lowest CFF threshold was observed within the 44-45 years age group (35.4 Hz; (Kaur et al., 2020)). Another study measured the mean CFF threshold in individuals > 65 years of age. The participants were split into an Alzheimer's disease group and a control group. The mean CFF value was significantly lower in the Alzheimer's disease group than the control group (36.4 ± 7.0 Hz versus 44.2 ± 3.8 Hz, $p < 0.001$, respectively; (Abiyev et al., 2022)). The CFF thresholds measured in these studies suggest that the Bernell pocket CFF tester may not be able to detect some of the lower CFF thresholds which are present amongst an older population.

The Bernell pocket CFF tester measures CFF through the method of limits; this method is known to be inefficient and participants are more likely to experience anticipation error when the flicker is close to being imperceptible by responding too early, however, it appears as though the HF-II also employs this method to measure CFF (Neitz, 2022). The CFF thresholds measured in the study ranged from 42 to 53 Hz. This corresponds with other studies which have shown human CFF thresholds to vary ranging from 10 to 60 Hz, 22 to 90 Hz, 40 to 60 Hz and 50 to 90 Hz (Różanowski et al., 2015, Muth et al., 2023). The variation in CFF measurements has been attributed to the participants and different instrumentation and methods used (Muth et al., 2023).

When measuring reliability of instrumentation and testing intraexaminer repeatability, previous studies have taken three consecutive measurements (Rouse et al., 2002, Johns et al., 2004, Tian et al., 2016, Cai et al., 2023, Wang et al., 2023) on two (Rouse et al., 2002, Antona et al., 2015, Wang et al., 2023) or three separate visits (Ekici et al., 2022). In the study, three consecutive measurements of CFF were taken (the average CFF value was used during data analysis) on three separate visits. The findings of the study show that three separate visits was unnecessary as acceptable levels of intraexaminer repeatability and reproducibility were achieved after the first and second visits, therefore future researchers only need to take three consecutive measurements on two separate visits for stable baseline data.

Sensitivity to change is defined as the ability of an instrument to measure a change in state, regardless of whether the change is relevant or meaningful whereas responsiveness is defined as the ability of an instrument to measure a meaningful change in a clinical state (Hasegawa et al., 2021). As there are no established methods to change the CFF threshold within an individual, a limitation of this study was it was not possible to measure sensitivity to change or responsiveness with the Bernell pocket CFF tester. However, as the CFF measurements were shown to be repeatable across the three separate visits, it suggests the repeatability was not due to an insensitive measure. Another limitation of the study was the age and type of participants included. As noted earlier, CFF thresholds tend to decrease with age; however, this study did not measure lower CFF thresholds, as the participants were predominantly young adults from a university setting (average age 29.9 ± 11.0 years). As a result, the Bernell pocket CFF tester showed high intraexaminer repeatability and reproducibility only in the mid to high CFF range (42 to 53 Hz). Given that the Bernell pocket CFF tester can only measure CFF thresholds between 35 Hz and 60 Hz, it may not be suitable for assessing CFF thresholds in older populations. Further research may be needed to evaluate the tester's repeatability and reproducibility in a more diverse, older sample.

3.6 Conclusion

The study demonstrated that the Bernell Pocket CFF Tester exhibits good intraexaminer repeatability and reproducibility. Given these reliable performance characteristics, it was confidently utilised to assess CFF thresholds in the subsequent chapters of the thesis.

Chapter 4. Privacy screen filters do not provide any benefit to digital eye strain sufferers after an intensive 30-minute laptop task

4.1 Introduction

Across the population, digital devices are used extensively for both social and / or professional purposes. Cybercrime hacking is the unauthorised use of, or access into, computers or networks by using security vulnerabilities or bypassing usual security steps to gain access (CPS, 2022). In 2022, 39 % of UK businesses identified a cyber-attack and the financial losses incurred ranged from £4,200 to £19,400 (Department for Digital Culture Media and Sport., 2022).

Visual hacking is the physical act of viewing and capturing sensitive, confidential, and private information for unauthorised use (Barker, 2019). In 2016, a global study found that visual hacking occurred in all countries and 91 % of 157 visual hacking trials were successful (PonemonInstitute, 2016). To reduce visual hacking, several manufacturers have produced privacy screen filters which can be easily applied onto smartphones, tablets, laptops, and desktop computer monitors.

As discussed in Chapter 1, privacy screen filters work by restricting the viewing angle of the device by using tiny, polarised blinds, known as micro louvers, that block out light from certain angles. Depending on the make and model, privacy screen filters usually start to block visibility at around a 30-degree side angle and may appear blacked-out near a 60-degree angle (Nelson, 2019). Privacy screen filters are usually comprised of multiple layers including a protective outer layer, anti-reflection coating, UV hard coating, polyester film, micro louvers, silicone adhesive, and a rear layer which comes in contact with the screen (Figure 4.1). The total thickness of a privacy screen filter is between 0.3 to 0.6 mm.

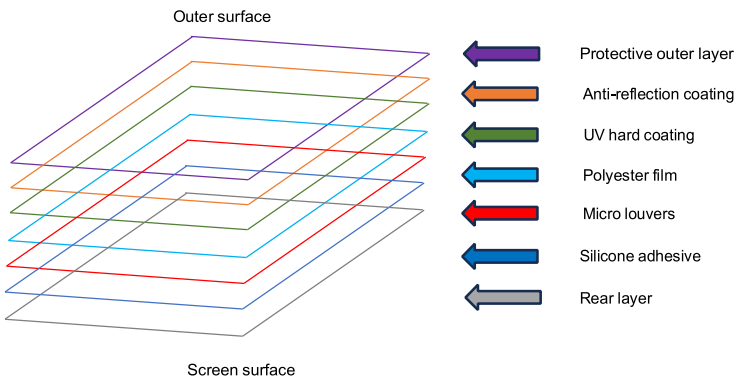


Figure 4.1. Schematic of a typical privacy screen filter construction.

Digital eye strain (DES), also known as computer vision syndrome has been a recognised health problem for over twenty years and has high prevalence levels; values of up to 98 % have been reported in adults, but around 72 % is more typical (Wolffsohn et al., 2023). Over the years, numerous studies have been conducted to determine if anti-reflection screens and / or filters reduce the symptoms of visual fatigue (Scullica et al., 1995, Hladký and Procházka, 1998, Sheedy et al., 2003, Reddy et al., 2013, Shantakumari et al., 2014, Ranasinghe et al., 2016a); the results have been mixed (Table 4.1).

Privacy screen filters tend to possess anti-reflection properties which may help reduce DES. Reflected glare, which can be caused by sunlight, overhead lights, and task lamps causes images to form at distances other than that of the screen surface; this can negatively impact the user's binocular vision system as ocular accommodation and convergence tend to fluctuate leading to symptoms of visual fatigue and reduced task performance (Shieh, 2000). Some privacy screen filters also have blue light reduction properties. For many years, blue light has been associated with retinal phototoxicity (Ham et al., 1976, Jaadane et al., 2015). Blue light-filtering spectacle lenses have been shown to reduce phototoxicity by 10.6 % to 23.6 % so could be used as a supplementary aid to protect the retina from potentially hazardous blue light (Leung et al., 2017). In contrast, another study has suggested that long-term viewing of blue light does not represent a biohazard (O'Hagan et al., 2016). Research is currently ongoing within this area but currently there is no evidence to support the use of blue-blocking filters as a clinical treatment for DES (Rosenfield et al., 2020, The College of Optometrists., 2022).

At the time of writing, there does not appear to be any published research measuring the impact of commercially available privacy screen filters on DES. Aston University was approached by a leading science-based technology company to test their novel privacy screen filter against one of their earlier generation privacy screen filters and a clear placebo filter, to determine if it reduces DES symptoms when using a laptop (Figure 4.2). Due to Intellectual Property and Confidentiality Laws, Aston University was not provided with any detailed product specifications other than the novel filter enables an average of 85 % transmission of the device's brightness and improves screen brightness by 25 % on average compared to competing "black" privacy filters. A noticeable difference between the 2 filters was their thickness (Figure 4.3). A USB digital microscope with a 2.0 MP camera and up to 500 X magnification was used to measure the thickness of the filters. Measurements were made through the installed measurement programme in Windows. The thickness of the novel privacy screen filter was measured as 0.57 mm whereas the earlier generation privacy screen filter was slightly thinner at 0.35 mm.

a. Novel privacy screen filter

b. Earlier generation privacy screen filter

Figure 4.2. Photographs of the novel privacy screen filter (a) and earlier generation privacy screen filter (b).

a. Novel privacy screen filter

b. Earlier generation privacy screen filter

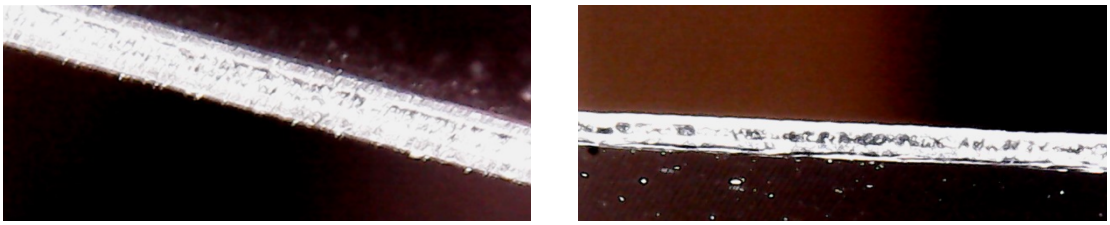


Figure 4.3. Thickness of the novel privacy screen filter (a) and earlier generation privacy screen filter (b) captured by a USB digital microscope.

Author and year	Participants completing the study	Mean age (years)	Task	Measures	Findings
Scullica *et al*. (1995)	Men, N = 16,302 Women, N = 8,762 Total, N = 25,064	38.9 ± 8.6 41.0 ± 9.2 39.4 ± 8.9	Mainly monochrome visual display unit (VDU) viewing with (28%) and without (72%) a filter during usual working hours.	Frequency of visual and ocular symptoms in participants with equal percentages of weekly working hours spent at a VDU.	Filters had no effect on the occurrence of asthenopia.
Hladký and Procházka, (1998)	Total, N = 60	Unknown	VDU viewing with (N = 40) or without (N = 20) a filter for their usual working hours.	Occurrence, duration, and intensity of ocular and physical symptoms.	No change in controls. Filter group reported less occurrence, shorter duration, and less intensive ocular and musculoskeletal complaints after one month of filter use.
Sheedy *et al*. (2003)	Total, N = 20	26.6 ± 4.8	Cathode-ray tube (CRT) display and liquid crystal display (LCD) matched exactly for display size and pixel count. 4 filter conditions:	Before the task: Best-corrected visual acuity, ocular history, and binocular vision measurements. During the task: Legibility, reading speed, letter counting	CEFs decreased both luminance and contrast when applied to the displays with the brightness set high, although contrast was better with filters compared to a matched

			1. No contrast enhancing filter (CEF) with high display brightness. 2. No CEF, low display brightness to match CEF2. 3. CEF1 (filter transmittance = 91.3 %), high brightness setting. 4. CEF2 (filter transmittance =82.5 %), high brightness setting.	speed, and participant comfort were measured for each filter condition.	luminance display without a filter. Performance on reading and letter counting tasks not improved with CEFs.
Reddy *et al*. (2013)	Men, N = 313 Women, N = 482 Total, N = 795	Unknown Unknown 21.3	A cross-sectional questionnaire survey.	Demographic details, spectacle use, computer use, digital eye strain (DES) symptoms, measures practiced to prevent eye problems, use of a screen filter, and room lighting.	Filters did not reduce DES symptoms.
Shantakumari *et al*. (2014)	Total, N = 500	20.4 ± 3.2	Self-administered questionnaire.	Demographic characteristics, computer usage and associated visual symptoms.	Sustained periods of close screen work without filters were associated with visual symptoms and

					increased interruptions of work.
Ranasinghe *et al*. (2016)	Total, N = 2210	30.8 ± 8.1	Self-administered questionnaire.	Socio-demographic data, DES symptoms, computer usage, potential risk factors, current workstations and knowledge on ergonomics and ergonomic practices. Individual workstations were evaluated using the Occupational Safety and Health Administration (OSHA) VDU workstation checklist.	Female gender, longer duration of occupation, higher daily computer usage, pre-existing eye disease, not using a filter, use of contact lenses and poor ergonomics were all associated with DES.

Table 4.1. Table showing previous studies that have assessed the effect of anti-reflection screens / filters on digital eye strain / visual fatigue.

4.2 Materials and methods

4.2.1 Participants

The study adhered to the tenets of the Declaration of Helsinki of 1975 and was approved by Aston University's Health and Life Sciences Research Ethics Committee (reference number HLS1822). Participants were recruited from both Aston University and the general public, and were enrolled following explanation of the study and after providing written consent. Participants were eligible for inclusion in the study if they were aged 18 years or older and classified as experiencing DES, based on the Computer Vision Syndrome Questionnaire (CVS-Q) score of ≥ 6 at baseline (Seguí Mdel et al., 2015). Pregnant women, and any individuals with new or unstable general health conditions and / or medications and / or eye disease were excluded from the study. A total of 21 participants were recruited. 14 were female and the average age was 33.8 ± 12.4 years. Their spherical equivalent (SE) prescriptions ranged from +0.75 D to -9.25 D (average -2.20 ± 3.23 D).

4.2.2 Examination protocol

The study was a prospective, repeated measures study where each participant served as their own control. The participants were masked, and the investigator was partially masked. The study comprised of 3 visits completed on separate days and each participant attended their visits at approximately the same time (mean time difference between visits = 0.4 ± 2.1 hours). Assessments were conducted in the same room, with room temperature of 21.2 ± 1.0 °C and relative humidity of 45.6 ± 10.8 %.

The same laptop (Lenovo ThinkPad T14) was used throughout the study (14" screen size, 1920 x 1200 screen resolution and set at 150 cd/m^2 luminance prior to having the screen filters applied) and the laptop screen had either a clear placebo filter, a novel privacy screen filter or an earlier generation privacy screen filter applied onto it. Since the filters had different light transmission levels, participants would have experienced varying screen brightness, though this remained consistent for each filter. The laptop was viewed from a 50 cm working distance (Rosenfield et al., 2009, Chu et al., 2011, Portello et al., 2013, Chu et al., 2014) with the room lights on and participants wore their habitual (updated within the last 2 years) refractive correction throughout (Rosenfield, 2011). Participants were instructed not to talk or look away from the screen during the task.

4.2.2.1 Task design

The task involved participants identifying a target letter (N) from a 5x5 grid of letters. Participants were presented with a Microsoft Word document (100% zoom level) containing 5x5 grids (each grid measured 5.95 cm x 5.95 cm) with no visible borders (Figure 4.4). The grids contained the target letter 'N' and non-target (distractor) letters (K, H, Z, W, M, V). The letters 'K, H, Z, W, M, V' are heterogeneous and share features with the target letter (Benoni and Tsal, 2013); this increases the task's extraneous load as the letters are not easily filtered out resulting in active searching during the task.

In the task, the target letter 'N' was either present or missing. In the condition where the target letter was present, the task had 24 non-target letters 'K, H, Z, W, M, V' located within the grid. In the condition where the target letter was missing, the task contained 25 nontarget letters 'K, H, Z, W, M, V' located within the grid. A Microsoft Excel (Microsoft, Redmond, WA, USA) random number generator was used to determine the position of every letter within the grids. The option to select 'N is missing' was available during the task.

Figure 4.4. Example of the digital task used during the study.

4.2.2.2 Participant interaction

As the investigator was partially masked, the screen filters were numbered 1, 2, and 3 by a colleague within the optometry department. An online random number generator was used to determine which screen filter the participant would use at the first visit. Participant details were confirmed including current refractive status, any known eye diseases / infections / treatment, any new and / or unstable general health conditions, and any newly prescribed

medications used. At baseline, participants were asked to complete the CVS-Q questionnaire and had their visual acuity, binocular vision status, ocular alignment, accommodation, convergence, critical flicker-fusion frequency (CFF), ocular surface, and tear film assessed (Table 4.2). Once baseline measurements were completed, the participants started the task.

Consistent instructions were given to participants - they were asked to highlight the target letter 'N' by using the Microsoft Word text highlighter tool. If they could not identify the letter 'N', they were asked to highlight 'N is missing'. If they made a mistake, they were told not to correct it and to move onto the next task. The task duration was 30-minutes. It was a continuous task and participants were not permitted to look away from the screen or talk during the task. At the end of every 10-minute time block, whilst still viewing the task, participants' static refraction, dynamic accommodation, and pupil size were measured using the Grand Seiko WAM-5500 (Hiroshima, Japan), see table 4.3. The Grand Seiko WAM-5500 was used as it is a reliable and valid objective refraction tool (Sheppard and Davies, 2010). At the end of the task, symptomology, CFF, near fixation disparity and accommodative facility were re-assessed (Table 4.4).

Parameters measured before the task	Tests performed
Symptomology	CVS-Q questionnaire
Habitual binocular distance visual acuity	LogMAR chart at 3 metres
Habitual binocular vision status	Near cover test and near fixation disparity (Mallett unit) at 50 cm
Accommodation	Accommodative facility (± 2.00 flippers) at 50 cm
Near point of convergence	RAF rule
Critical flicker-fusion frequency	Bernell pocket CFF tester at 40 cm
Ocular surface and tear film (right eye only)	Oculus Keratograph 5M

Table 4.2. Measurements taken before the 30-minute continuous digital task.

Parameters measured during the task at every 10-minute interval for 30-minutes. (Measurements taken from the right eye only)	Tests performed
Static refraction	Grand Seiko WAM-5500
Dynamic refraction	Grand Seiko WAM-5500 (dynamic mode ~5.0 Hz sampling)
Pupil size	Grand Seiko WAM-5500

Table 4.3. Measurements taken during the digital task at every 10-minute interval for 30-minutes.

Parameters measured after the task	Tests performed
Symptomology	CVS-Q questionnaire
Habitual binocular vision status	Near cover test and near fixation disparity (Mallett unit) at 50 cm
Accommodation	Accommodative facility (± 2.00 flippers) at 50 cm
Critical flicker-fusion frequency	Bernell pocket CFF tester at 40 cm

Table 4.4. Measurements taken after the 30-minute continuous digital task.

4.3 Statistical analysis

Sample size requirements were based on the primary outcome measure of a change in symptomology (CVS-Q score) determined by G*Power software (version 3.1.9.7); a minimum sample size of 20 participants was suggested with 0.25 effect size, 80 % power and 5 % significance level ($\alpha = 0.05$). A greater sample size was recruited in case of any participant attrition during the study.

The data were analysed with SPSS (Version 25, SPSS Inc, Chicago, II, USA). Data that were found to be normally distributed (CVS-Q, CFF, and dynamic pupil size; one-sample Kolmogorov Smirnov test $p > 0.05$) had parametric, repeated-measure (ANOVA) and Pearson correlation tests applied. Metrics where the data were not normally distributed (near fixation disparity, accommodative facility, and dynamic within-task accommodation: one-sample Kolmogorov Smirnov test $p < 0.05$), had non-parametric, repeated-measure Wilcoxon, Friedman and Spearman rank correlation tests applied. Values of $p < 0.05$ were taken as statistically significant.

4.4 Results

4.4.1 Pre and Post Task Measures

Symptomology (CVS-Q score) reduced in severity after 30-minutes of screen viewing ($F = 8.069$, $p = 0.010$) but the effect was similar between the three filters ($F = 0.206$, $p = 0.815$).

Critical flicker-fusion frequency ($F = 0.772$, $p = 0.390$) and near fixation disparity ($df = 2$, $p = 0.717$) did not change after 30-minutes of screen viewing for any of the three filters.

The accommodative facility remained unchanged post-task for the novel privacy screen filter and earlier generation privacy screen filter but had significantly reduced ($p = 0.007$) in the clear placebo filter condition.

Filter	Variable	Mean ± SD pre-task	Mean ± SD post-task	Paired t-test *p* value / Wilcoxon test *p* value
Novel privacy screen filter	Symptomology	11.40 ± 3.93	9.75 ± 4.79	0.003 *
	Critical flicker-fusion frequency	47.60 ± 2.45	47.40 ± 1.97	0.568
	Near fixation disparity	0.34 ± 0.58	0.47 ± 0.68	0.186
	Accommodative facility	7.48 ± 4.21	7.14 ± 4.13	0.110
Earlier generation	Symptomology	10.75 ± 2.47	10.65 ± 3.95	0.885

privacy screen filter	Critical flicker-fusion frequency	47.55 ± 2.08	47.31 ± 2.03	0.319
	Near fixation disparity	0.34 ± 0.58	0.38 ± 0.59	0.329
	Accommodative facility	7.38 ± 4.12	7.10 ± 4.07	0.110
Clear placebo filter	Symptomology	10.70 ± 2.79	9.65 ± 3.67	0.024 *
	Critical flicker-fusion frequency	47.74 ± 2.22	47.57 ± 1.94	0.554
	Near fixation disparity	0.38 ± 0.59	0.38 ± 0.59	Unable to be calculated
	Accommodative facility	7.14 ± 4.13	6.52 ± 4.06	0.04 *

Table 4.5. Mean ± standard deviation and p values for the pre and post task measures for the different screen filters. Statistically significant results are marked by an asterisk (*).

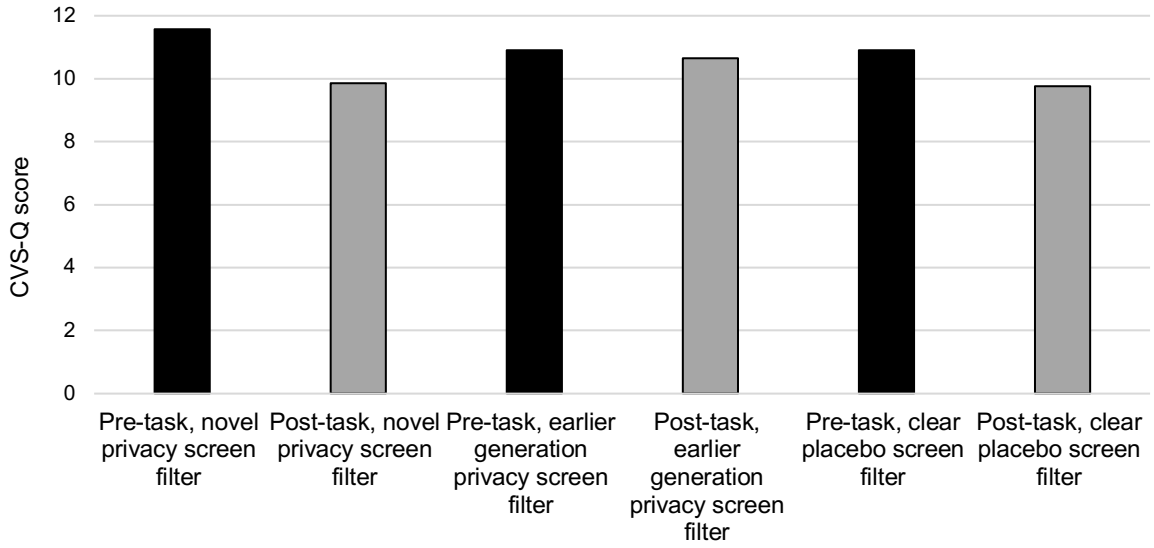


Figure 4.5. Bar chart showing the average pre- and post-task symptomology (CVS-Q) scores after 30-minutes for the three different filter conditions.

4.4.2 Within Task Measures

Pupil size did not change during the 30-minutes of screen viewing for any of the three filters ($F = 2.065$, $p = 0.144$) but the pupil size was significantly larger during the task with the

earlier generation privacy screen filter compared to the clear placebo filter (F = 7.794, p = 0.012).

After 10-minutes of viewing the task, the mean of the accommodative response during the dynamic recording was greater with the novel privacy screen filter compared to the clear placebo filter (df = 1, p < 0.001) but no difference was observed between any of the three filters at 20-minutes (df = 2, p = 0.368) nor at 30-minutes (df = 2, p = 0.534).

4.4.3 Effect of Age

When using any of the three filters, there was no significant correlation (r = -0.05 to 0.09, p > 0.05) between the difference in post-task symptomology (CVS-Q score) with the participant's age. When using the novel privacy screen filter and the earlier generation privacy screen filter, there was a non-significant, moderately negative correlation (r = -0.881 to -0.571, p > 0.01) between the difference in the critical flicker-fusion frequency, near fixation disparity and accommodative facility with the participant's age. When using the clear placebo filter, there was a significant, moderately to high negative correlation (r = -0.908 to -0.666, p < 0.01) between the difference in post-task critical flicker-fusion frequency, near fixation disparity and accommodative facility with the participant's age.

Filter	Symptomology	Critical flicker-fusion frequency	Near fixation disparity	Accommodative facility
Novel privacy screen filter	r = -0.05 p = 0.816	r = -0.589 p = 0.787	r = -0.666 p = 0.436	r = -0.633 p = 0.932
Earlier generation privacy screen filter	r = 0.02 p = 0.918	r = -0.571 p = 0.534	r = -0.881 p = 0.366	r = -0.684 p = 0.352
Clear placebo filter	r = 0.09 p = 0.706	r = -0.785 p < 0.01 *	r = -0.908 p < 0.01 *	r = -0.666 p < 0.01 *

Table 4.6. Spearman correlation coefficient (r) and significance (p) values for the difference in post-task measures compared to the participant's age for the different screen filters. Statistically significant results are marked by an asterisk (*).

4.5 Discussion

The purpose of the current study was to determine if a novel privacy screen filter reduces DES symptoms when using a laptop compared to an earlier generation privacy screen filter and a clear placebo filter. A robust, repeated measures, randomised controlled trial design was applied with the researcher and participants masked as to the filters used at each visit. The most commonly used DES questionnaire (CVS-Q) was utilised to assess symptoms before and after an intensive 30-minute task, used to stress the visual system. In addition, measures of visual stress (CFF), eye focus fatigue (accommodative facility) and eye vergence fatigue (near fixation disparity) were assessed. Although eye focus fatigue was seen to occur with the task, there was no significant difference between the novel and earlier generation privacy filter or compared to the clear placebo filter. With increasing age, accommodative facility and CFF threshold values tend to be lower (Siderov and DiGuglielmo, 1991, Kaur et al., 2020). There does not appear to be any research showing that accommodative facility and CFF thresholds worsen in older individuals any more than that of younger individuals after digital screen use. In the present study, no association with age was found when using the novel and earlier generation privacy screen filters, but this is not surprising given the limited changes seen. Dynamic measures of eye focus and pupil size were taken during the task at 10-minute intervals to ascertain whether there were more subtle changes during the task, but again no significant difference was observed between the novel and earlier generation privacy filter or compared to the clear placebo filter. In conclusion, the study has not been able to provide evidence of a benefit of privacy filters for people who experience DES.

As shown in table 4.1, the findings of this study are consistent with two previously performed studies. Scullica *et al*. (1995) and Reddy *et al*. (2013) both found that screen filters do not reduce symptoms of asthenopia and DES. In contrast, Hladký and Procházka (1998), Shantakumari *et al*. (2014) and Ranasinghe *et al*. (2016) all reported that screen filters do reduce symptoms of DES. With continuing technological advances and the move away from cathode ray tube (CRT) displays, early studies of DES such as Scullica *et al*. (1995) and Hladký and Procházka (1998) may be less relevant today. When comparing the findings against Shantakumari *et al*. (2014) and Ranasinghe *et al*. (2016), it is important to note that Shantakumari *et al*. (2014) and Ranasinghe *et al*. (2016) collected data through self-adminstered questionnaires. In contrast, this study was in-person and participants were masked.

The clear placebo filter was recognisable to the investigator as it did not block screen visibility from a 30-degree side angle. Even though the investigator knew the characteristics of the clear placebo filter, the participants did not. The improvement of symptoms after the 30-minute task was unexpected; this was attributed to the placebo effect as the participants were aware that screen filters had been applied onto the laptop and may have expected the filters to help their symptoms. As the effect was similar between all three filters, the results demonstrated the importance of having the clear placebo filter as one of the conditions as it was determined that the privacy filters did not have a specific effect on symptomology. Despite the 30-minute task being a similar duration to previous DES studies (Collier and Rosenfield, 2011, Palavets and Rosenfield, 2019, Gautam, 2020, Redondo et al., 2020, Rosenfield et al., 2020, Padavettan et al., 2021, Lin et al., 2022, Talens-Estarelles et al., 2022b, Yan and Rosenfield, 2022), the DES symptoms had not worsened by the end of the task; this prompted a second study with a longer, 60-minute task duration (Chapter 5).

4.6 Conclusion

Previous studies have provided conflicting findings on whether the use of screen filters help alleviate DES symptoms. The present study has not been able to provide evidence of a benefit of new generation privacy screen filters for people who experience DES when completing a 30-minute intensive task.

Chapter 5. Privacy screen filters do not provide any benefit to digital eye strain sufferers after an intensive 60-minute laptop task

5.1 Introduction

In the previous chapter, it was observed that DES symptoms did not significantly worsen at the end of an intensive 30-minute continuous digital task. The findings prompted a follow-up study that extended the task duration to 60-minutes.

Digital screen time, or the time spent in front of digital screens, has become an integral part of modern life. Globally, the average daily screen time is reported to be 6 hours and 35 minutes (Kemp, 2024a). DES symptoms have been known to manifest as early as 20-minutes after initiating digital device use (Cardona et al., 2011) however there is a general consensus that prolonged screen time exacerbates the severity of DES symptoms, as summarised in Table 5.1.

Given these findings, the follow-up study aims to further investigate the relationship between prolonged screen time and DES, particularly focusing on whether a 60-minute task would lead to a more noticeable increase in symptoms. Additionally, the use of a novel privacy screen filter represents an innovative approach to potentially mitigating these effects. The study outlined in this chapter will contribute to a deeper understanding of how extended screen time impacts DES symptoms and whether commercially available interventions can provide relief.

Author and year	Participants completing the study	Mean age (years)	Type of study	Measures	Screen time duration	Findings
Cardona *et al*. (2011)	N = 25	24.4 ± 1.7	Experimental	Blink rate, blink amplitude, tear film integrity, and questions about visual fatigue and ocular dryness.	20-minutes Symptoms were assessed at the end of the 20-minute task.	After 20-minutes, a negative impact on blinking characteristics, tear film integrity, visual fatigue, and ocular comfort was observed.
Portello *et al*. (2012)	N = 520	39.3	Survey	Hayes *et al*. (2007) visual symptoms questionnaire.	Not applicable.	A significant correlation was observed between the total symptom score and the number of hours spent working on a computer in a typical day.

Reddy *et al*. (2013)	N = 795	21.3	Survey	A questionnaire including demographic details, spectacles use, computer use, symptoms of digital eye strain (DES), any measures practiced preventing eye problems, use of a radiation filter, and room lighting.	Not applicable.	Digital device usage > 2 hours per day was associated with significantly more DES symptoms.
Ayyakutty Muni Raja (2015)	N = 300	Not given	Survey	A questionnaire including demographic details, duration of computer usage per day, years of computer use, working distance from computer, level of top of screen from eye level, use of antiglare screen, brightness and contrast adjustment and taking breaks during computer use.	Not applicable.	Digital device usage between 6-9 hours per day was associated with significantly more DES symptoms.
Kim *et al*. (2016)	N = 715	Not given	Survey	Smartphone use and visuo-ocular symptoms questionnaire.	Not applicable.	Increased ocular discomfort and visual symptoms occurred when using smartphones > 2 hours per day.

Kamal and El-Mageed (2018)	N = 218	38.9 ± 9.9	Survey	A pre-tested structured questionnaire, personal interview and inspection of workstations.	Not applicable.	Digital device usage > 4 hours per day was associated with significantly more DES symptoms.
Tesfa *et al*. (2019)	N = 217	32.3 ± 6.0	Survey	A visuo-ocular symptoms questionnaire.	Not applicable.	Participants using digital devices ≥ 6 hours per day were three times more likely to have DES than those who used devices for < 6 hours per day.
Golebiowski *et al*. (2020)	N = 12	18.5	Experimental	Ocular symptoms (Eyestrain Symptoms Questionnaire and Numerical Rating Scale), tear function and binocular vision.	1-hour Symptoms were assessed before and after the 1-hour task.	Ocular symptoms were significantly worse after 1-hour of reading on a smartphone.

Touma Sawaya *et al*. (2020a)	N = 457	19.8	Survey	A self-administered questionnaire regarding demographics, current major and faculty, usage of digital device, type of device and time spent using it, reason for using the digital device, use of glasses or contact lenses, symptoms of asthenopia and preventive measures.	Not applicable.	Digital device usage > 4 hours per day was associated with significantly more asthenopia symptoms.
Alabdulkader (2021)	N = 1,939	33.0 ± 12.2	Survey	A self-reported questionnaire regarding digital device usage and DES symptoms.	Not applicable.	Prolonged digital device usage > 6 hours per day was associated with increased DES symptoms.
Cantó-Sancho *et al*. (2021)	N = 244	20.7 $\pm$ 2.1	Survey	Medical history, visual display terminal (VDT) exposure questionnaire, and Computer Vision Syndrome Questionnaire (CVS-Q).	Not applicable.	Digital device usage > 4 hours per day was associated with an increased likelihood of DES compared with digital device usage < 2 hours per day.

Gammoh (2021)	N = 382	21.5 ± 1.8	Survey	CVS-Q.	Not applicable.	A positive association was observed between hours spent on digital devices and DES symptoms.
Mohan *et al*. (2021)	N = 217	13.0 ± 2.5	Survey	Electronic survey form asking about digital device usage before and during the COVID era, and the CVS-Q.	Not applicable.	A positive association was observed between use of digital devices > 5 hours per day and use of mobile games > 1 hour per day and DES symptoms.
Zayed *et al*. (2021)	N = 108	32.2 ± 6.0	Survey	A questionnaire pertaining to socio-demographic, job, ergonomic and environmental characteristics and the CVS-Q.	Not applicable.	Digital device usage ≥ 6 hours per day was a significant predictor of DES.

Chu *et al*. (2023)	N= 1298	10.9 ± 2.0	Survey	Hayes *et al*. (2007) visual symptoms survey, time spent on smartphones and tablets per day, and body mass index (BMI).	Not applicable.	Participants with baseline smartphone usage of 3-4 hours per day had a significantly higher 1-year follow-up DES score than those with baseline smartphone usage of < 1 hour per day.

Table 5.1. Previous studies investigating the effect of the time spent on digital devices and digital eye strain (DES) symptoms.

5.2 Materials and methods

5.2.1 Participants

The study adhered to the tenets of the Declaration of Helsinki of 1975 and was approved by Aston University's Health and Life Sciences Research Ethics Committee (reference number HLS1822). Participants were recruited from both Aston University and the general public, and were enrolled following explanation of the study and after providing written consent. Participants were eligible for inclusion in the study if they were aged 18 years or older and classified as experiencing DES, based on the Computer Vision Syndrome Questionnaire (CVS-Q) score of ≥ 6 at baseline (Seguí Mdel et al., 2015). Pregnant women, and any individuals with new or unstable general health conditions and / or medications and / or eye disease were excluded from the study. A total of 20 participants were recruited. 12 were female and the average age was 28.3 ± 9.6 years. Their spherical equivalent (SE) prescriptions ranged from +3.00 to -7.25 D (average -1.29 ± 2.33 D).

5.2.2 Examination protocol

The same examination protocol as used in the previous privacy screen filter study (Chapter 4, section 4.2.2) was implemented, with the only modification being a doubling of the task duration to 60 minutes. Within-task measures were taken at 20-, 40-, and 60-minutes. The study was a prospective, repeated measures study where each participant served as their own control. The participants were masked, and the investigator was partially masked. The study comprised of 3 visits completed on separate days and each participant attended their visits at approximately the same time (mean time difference between visits = 1.8 ± 1.8 hours). Assessments were conducted in the same room, with room temperature of 20.6 ± 1.4 °C and relative humidity of 32.6 ± 5.9 %.

The same laptop (Lenovo ThinkPad T14) was used throughout the study (14" screen size, 1920 x 1200 screen resolution and set at 150 cd/m^2 luminance prior to having the screen filters applied) and the laptop screen had either a clear placebo filter, a novel privacy screen filter or an earlier generation privacy screen filter applied onto it. Since the filters had different light transmission levels, participants would have experienced varying screen brightness, though this remained consistent for each filter. The laptop was viewed from a 50 cm working distance (Rosenfield et al., 2009, Chu et al., 2011, Portello et al., 2013, Chu et al., 2014) with the room lights on and participants wore their habitual (updated within the last

2 years) refractive correction throughout (Rosenfield, 2011). Participants were instructed not to talk or look away from the screen during the task.

5.2.2.1 Task design

The same task design as the previous privacy screen filter study was implemented. The task involved participants identifying a target letter (N) from a 5x5 grid of letters. Participants were presented with a Microsoft Word document (100% zoom level) containing 5x5 grids (each grid measured 5.95 cm x 5.95 cm) with no visible borders (Figure 5.1). The grids contained the target letter 'N' and non-target (distractor) letters (K, H, Z, W, M, V). The letters 'K, H, Z, W, M, V' are heterogeneous and share features with the target letter (Benoni and Tsal, 2013); this increases the task's extraneous load as the letters are not easily filtered out resulting in active searching during the task.

In the task, the target letter 'N' was either present or missing. In the condition where the target letter was present, the task had 24 non-target letters 'K, H, Z, W, M, V' located within the grid. In the condition where the target letter was missing, the task contained 25 nontarget letters 'K, H, Z, W, M, V' located within the grid. A Microsoft Excel (Microsoft, Redmond, WA, USA) random number generator was used to determine the position of every letter within the grids. The option to select 'N is missing' was available during the task.

Figure 5.1. Example of the digital task used during the study.

5.2.2.2 Participant interaction

As the investigator was partially masked, the screen filters were numbered 1, 2, and 3 by a colleague within the optometry department. An online random number generator was used

to determine which screen filter the participant would use at the first visit. Participant details were confirmed including current refractive status, any known eye diseases / infections / treatment, any new and / or unstable general health conditions, and any newly prescribed medications used. At baseline, participants were asked to complete the CVS-Q questionnaire and had their visual acuity, binocular vision status, ocular alignment, accommodation, convergence, critical flicker-fusion frequency (CFF), ocular surface, and tear film assessed (Table 5.2). Once baseline measurements were completed, the participants started the task.

Consistent instructions were given to participants - they were asked to highlight the target letter 'N' by using the Microsoft Word text highlighter tool. If they could not identify the letter 'N', they were asked to highlight 'N is missing'. If they made a mistake, they were told not to correct it and to move onto the next task. The task duration was 60-minutes. It was a continuous task and participants were not permitted to look away from the screen or talk during the task. At the end of every 20-minute time block, whilst still viewing the task, participants' static refraction, dynamic accommodation, and pupil size were measured using the Grand Seiko WAM-5500 (Hiroshima, Japan), see table 5.3. The Grand Seiko WAM-5500 was used as it is a reliable and valid objective refraction tool (Sheppard and Davies, 2010). At the end of the task, symptomology, CFF, near fixation disparity and accommodative facility were re-assessed (Table 5.4).

Parameters measured before the task	**Tests performed**
Symptomology	CVS-Q questionnaire
Habitual binocular distance visual acuity	LogMAR chart at 3 metres
Habitual binocular vision status	Near cover test and near fixation disparity (Mallett unit) at 50 cm
Accommodation	Accommodative facility (± 2.00 flippers) at 50 cm
Near point of convergence	RAF rule
Critical flicker-fusion frequency	Bernell pocket CFF tester at 40 cm

Ocular surface and tear film (right eye only)	Oculus Keratograph 5M

Table 5.2. Measurements taken before the 60-minute continuous digital task.

Parameters measured during the task at every 20-minute interval for 60-minutes. (Measurements taken from the right eye only)	**Tests performed**
Static refraction	Grand Seiko WAM-5500
Dynamic refraction	Grand Seiko WAM-5500 (dynamic mode ~5.0 Hz sampling)
Pupil size	Grand Seiko WAM-5500

Table 5.3. Measurements taken during the digital task at every 20-minute interval for 60-minutes.

Parameters measured after the task	**Tests performed**
Symptomology	CVS-Q questionnaire
Habitual binocular vision status	Near cover test and near fixation disparity (Mallett unit) at 50 cm
Accommodation	Accommodative facility (± 2.00 flippers) at 50 cm
Critical flicker-fusion frequency	Bernell pocket CFF tester at 40 cm

Table 5.4. Measurements taken after the 60-minute continuous digital task.

5.3 Statistical analysis

Sample size requirements were based on the primary outcome measure of a change in symptomology determined by G*Power software (version 3.1.9.7); a minimum sample size of 20 participants was suggested with 0.25 effect size, 80 % power and 5 % significance level ($\alpha = 0.05$).

The data were analysed with SPSS (Version 25, SPSS Inc, Chicago, II, USA). Data that were found to be normally distributed (CVS-Q, CFF, dynamic pupil size and dynamic within-task accommodation; one-sample Kolmogorov Smirnov test $p > 0.05$) had parametric, repeated-measure (ANOVA) and Pearson correlation tests applied. Metrics where the data were not normally distributed (near fixation disparity and accommodative facility: one-sample Kolmogorov Smirnov test $p < 0.05$), had non-parametric, repeated-measure Wilcoxon, Friedman and Spearman rank correlation tests applied. Values of $p < 0.05$ were taken as statistically significant.

5.4 Results

5.4.1 Pre and Post Task Measures

Symptomology (CVS-Q score) worsened after 60-minutes of screen viewing ($F = 5.580$, $p = 0.008$) but the effect was similar between the three filters ($F = 4.296$, $p = 0.052$).

Near fixation disparity ($df = 5$, $p = 1.0$) did not change after 60-minutes of screen viewing for any of the three filters. There was a small but significant decrease for critical flicker-fusion frequency measures in the novel ($p = 0.035$) and clear placebo filter conditions ($p = 0.006$) but not for the earlier-generation filter ($p = 0.057$).

Accommodative facility worsened ($F = 5$, $p < 0.001$) after 60-minutes of screen viewing for all three filters.

Filter	Variable	Mean ± SD pre-task	Mean ± SD post-task	Paired t-test *p* value / Wilcoxon test *p* value
Novel privacy screen filter	Symptomology	9.1 ± 0.9	10.6 ± 1.2	0.034 *
	Critical flicker-fusion frequency	48.1 ± 0.4	47.3 ± 0.4	0.035 *
	Near fixation disparity	0.06 ± 0.2	0.06 ± 0.2	Unable to be calculated
	Accommodative facility	8.1 ± 2.9	7.3 ± 3.2	0.014 *

Earlier generation privacy screen filter	Symptomology	10.4 ± 1.0	11.0 ± 1.0	0.081
	Critical flicker-fusion frequency	48.0 ± 0.4	47.5 ± 0.4	0.057
	Near fixation disparity	0.06 ± 0.2	0.06 ± 0.2	Unable to be calculated
	Accommodative facility	7.7 ± 3.1	7.5 ± 3.2	0.028 *
Clear placebo filter	Symptomology	11.0 ± 1.1	11.2 ± 1.1	0.281
	Critical flicker-fusion frequency	48.1 ± 0.4	47.5 ± 0.5	0.006 *
	Near fixation disparity	0.06 ± 0.2	0.06 ± 0.2	Unable to be calculated
	Accommodative facility	8.1 ± 2.9	7.4 ± 3.2	0.020 *

Table 5.5. Mean ± standard deviation and the paired t-test p value for the pre and post task measures for the different screen filters. Statistically significant results are marked by an asterisk (*).

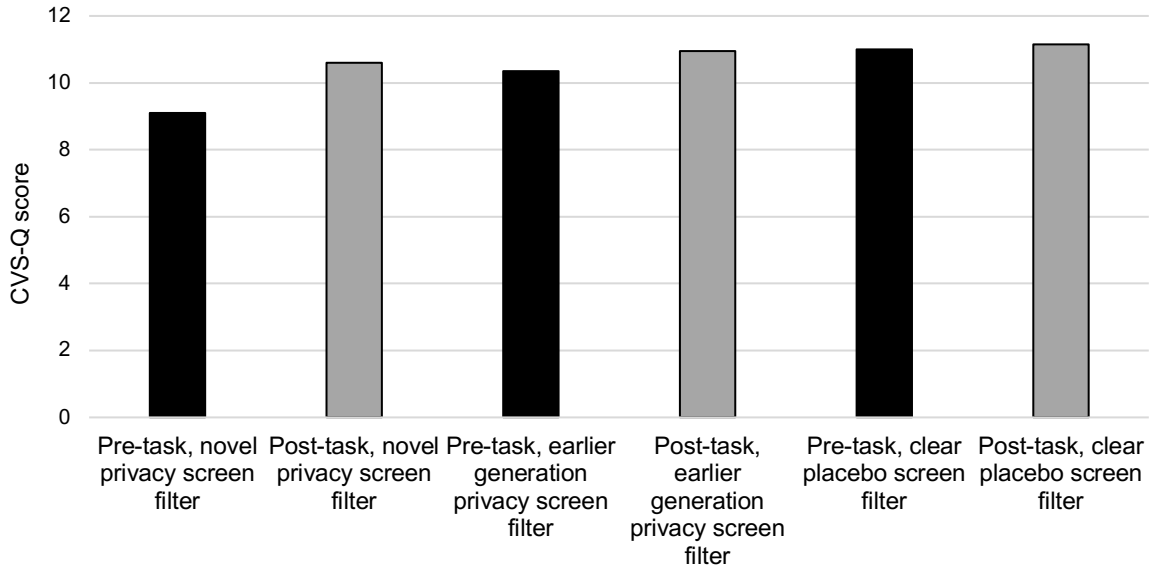


Figure 5.2. Bar chart showing the average pre- and post-task symptomology (CVS-Q) scores after 60-minutes for the three different filter conditions.

5.4.2 Within Task Measures

Pupil size increased during the 60-minutes of screen viewing for all three filters (F = 6.891, *p* = 0.003), but the increase in pupil size was similar between the three filters (F = 3.805, *p* = 0.07). Dynamic accommodation (F = 1.387, *p* = 0.268) did not change after 60-minutes of screen viewing for any of the three filters.

5.4.3 Effect of Age

When using any of the three filters, there was no significant correlation (r = -0.150 to 0.318, *p* > 0.05) between the difference in post-task symptomology (CVS-Q) with the participant's age. When using the novel privacy screen filter and the earlier generation privacy screen filter, there was no significant correlation (r = -0.129 to 0.317, *p* > 0.05) between the difference in critical flicker-fusion frequency and near fixation disparity with the participant's age. When using the novel privacy screen filter, there was a significant, moderately negative correlation (r = -0.530, *p* < 0.05) between accommodative facility and the participant's age, but when using the earlier generation privacy screen filter, there was no significant correlation (r = -0.302, *p* > 0.05) between accommodative facility and the participant's age. When using the clear screen filter, there was a significant, moderately positive correlation (r =0.489 to 0.702, *p* < 0.05) between critical flicker-fusion frequency, near fixation disparity and accommodative facility and the participant's age.

Filter	Symptomology	Critical flicker-fusion frequency	Near fixation disparity	Accommodative facility
Novel privacy screen filter	r = 0.0756 *p* = 0.751	r = -0.0398 *p* = 0.868	r = 0.317 *p* = 0.173	r = -0.530 *p* = 0.0163 *
Earlier generation privacy screen filter	r = -0.150 *p* = 0.527	r = 0.196 *p* = 0.407	r = -0.129 *p* = 0.587	r = -0.302 *p* = 0.196
Clear placebo filter	r = 0.318 *p* = 0.172	r = 0.489 *p* = 0.0288 *	r = 0.702 *p* = 0.000559*	r = 0.510 *p* = 0.0216 *

Table 5.6. Spearman correlation coefficient (r) and significance (p) values for the difference in post-task measures compared to the participant's age for the different screen filters. Statistically significant results are marked by an asterisk (*).

5.5 Discussion

The purpose of the current study was to determine if a novel privacy screen filter reduces DES symptoms when using a laptop compared to earlier generation privacy screen filters and a clear screen filter. A robust, repeated measures, randomised controlled trial design was applied with the researcher and participants masked as to the filters used at each visit. The most commonly used DES questionnaire (CVS-Q) was utilised to assess symptoms before and after an intensive 60-minute task, used to stress the visual system. In addition, measures of visual stress (critical flicker-fusion frequency), eye focus fatigue (accommodative facility) and eye vergence fatigue (near fixation disparity) were assessed.

In both studies (Chapters 4 and 5), the participants were masked. The investigator was only partially masked, as the clear placebo filter was distinguishable to them, since it did not block screen visibility from a 30-degree side angle. However, the participants were unaware of the characteristics of the clear placebo filter. To reduce bias, the filters were randomly assigned to participants during each visit, and the same experimental protocol was followed at every visit. The data was also analysed with partial masking; the filters were coded as 1, 2, and 3, with their identities revealed only after the data analysis was completed.

Parameter	**Chapter 4 (after the 30-minute task)**	**Chapter 5 (after the 60-minute task)**
Symptomology	Improved for all 3 filters	Worsened for all 3 filters
Critical flicker-fusion frequency	Unchanged for all 3 filters	Decreased in the novel and clear placebo filter conditions
Near fixation disparity	Unchanged for all 3 filters	Unchanged for all 3 filters
Accommodative facility	Worsened in the clear placebo filter condition	Worsened for all 3 filters
	During the 30-minute task	**During the 60-minute task**
Pupil size	Unchanged for all 3 filters	Increased for all 3 filters
Dynamic accommodation	Unchanged for all 3 filters after 20- and 30-minutes	Unchanged for all 3 filters

Table 5.7. Table comparing the results of Chapter 4 (30-minute task) and Chapter 5 (60-minute task).

At the end of the 60-minute task, DES symptoms had worsened, and eye focus fatigue was seen to occur (as evidenced by the accommodative facility and critical flicker-fusion frequency), however, there was no significant difference between the novel and earlier generation privacy filter or compared to the clear placebo filter. When using the novel privacy screen filter, there was a significant, moderately negative correlation between eye focus fatigue and the participant's age. No other association with age was found when using the novel and earlier generation privacy screen filters.
Dynamic measures of eye focus and pupil size were taken during the task at 20-minute intervals to ascertain whether there were more subtle changes during the task, but again no significant difference was observed between the novel and traditional privacy filter or compared to the clear placebo filter. In conclusion, the study has not been able to provide evidence of a benefit of privacy filters for people who experience DES.

In the first privacy screen filters study, DES symptoms had not worsened by the end of the 30-minute task. In this study, DES symptoms had significantly worsened for all three filters at the end of the 60-minute task (the same task was used in both studies). Although different participants were used in the two studies, these findings are consistent with previous studies which show a positive association between hours spent on digital devices and worsening DES symptoms (Table 5.1). In the 30-minute task group, pupil size did not change during screen viewing for any of the three filters and accommodative facility remained unchanged for the novel privacy screen filter and earlier generation privacy screen filter. In the 60-minute task group, pupil size increased during the task and accommodative facility worsened for all three filters. Changes in pupillary characteristics have been explored as potential indicators of visual fatigue (Sheppard and Wolffsohn, 2018). It has been shown that reading from screens tends to increase cognitive demands which subsequently causes the pupils to dilate (Querino et al., 2015) and after prolonged periods (2-hours) induces ocular instability (Di Stasi et al., 2013); these conflicting signals may result in visual fatigue (Miranda et al., 2018) which was seen as worsening DES at the end of the 60-minute task.

In both studies, there was no correlation between the difference in post-task symptomology with the participant's age; this corresponds with previous studies which have also shown no correlation between age and visual fatigue symptoms when viewing digital screens (Zargari Marandi et al., 2018, Larese Filon et al., 2019, Lin et al., 2021). The participants did not express a preference for any of the three filters which were used in the study.

Worldwide, the average daily screen time is reported to be 6 hours and 35 minutes (Kemp, 2024a). While a 60-minute task may not fully capture typical digital device usage, previous research has indicated that symptoms of DES begin to manifest after just 60 minutes of screen exposure (Cardona et al., 2011, Golebiowski et al., 2020), a trend which was also observed in the current study as DES symptoms significantly worsened for all three filters by the end of the 60-minute task. Although not directly tested, these results may also apply to longer usage durations, as earlier studies have shown that DES symptoms worsen with increased screen time (Table 5.1).

5.6 Conclusion

The findings of this study have shown that 60-minutes of continuous digital device usage causes DES symptoms to worsen but has not been able to provide evidence of a benefit of privacy screen filters for people who experience DES.

Chapter 6. Digital eye strain symptoms worsen during prolonged digital tasks, associated with a reduction in productivity

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Abstract

Purpose: It is often stated that digital eye strain can impact productivity and/or work accuracy, but the relationship between symptoms, productivity, and work accuracy has been unclear. Hence this study tracked the development of visuo-ocular symptoms during prolonged digital tasks and to explore the impact of higher and lower cognitive load levels on visuo-ocular symptoms, productivity, and work accuracy.
Methods: Thirty-five participants (23.2 ± 4.0 years) who had digital eye strain (diagnosed with the Computer Vision Syndrome Questionnaire) undertook an uninterrupted laptop adapted Eriksen Flanker task for 60 minutes on two separate days, once with a high cognitive load in randomised sequence. Symptoms were assessed at baseline and every 10 minutes throughout the task.
Results: All visuo-ocular symptom scores significantly worsened ($F = 87.783$, $p < 0.001$) with time, with the symptom severity increasing faster with the higher cognitive load ($F = 7.110$, $p < 0.001$). The mean total number of tasks completed was greater for the lower (1060.8 ± 296.5) than the higher (532.2 ± 123.4) cognitive load tasks ($F = 138.830$, $p<0.001$), reducing with time ($F = 7.339$, $p < 0.001$), but in a similar way for both cognitive loads ($F = 1.795$, $p = 0.154$). Task accuracy was not affected by the cognitive load of the task ($F = 1.729$, $p = 0.197$) and was consistent over time ($F = 1.885$, $p = 0.135$).
Conclusions: Symptoms increased with task duration in individuals with digital eye strain, with a faster rate for more demanding tasks. This was associated with a decrease in the task completion rate (productivity), but not the work accuracy.

6.1 Introduction

The use of digital devices is ubiquitous amongst all age groups, with hours of daily usage increasing significantly in recent years. Digital eye strain (DES), also known as computer vision syndrome, is defined as “the development or exacerbation of recurrent ocular symptoms and / or signs related specifically to digital device screen viewing” (Wolffsohn et al., 2023). The prevalence of the condition is high, with most studies in this field reporting prevalence levels between 50 % to over 90 % (Hayes et al., 2007, Sheppard and Wolffsohn, 2018, Kaur et al., 2022, Iqbal et al., 2023). Whilst symptoms are reversible, many people around the world are experiencing discomfort and detrimental visual effects whilst using digital devices for prolonged periods of time (Alabdulkader, 2021, Wolffsohn et al., 2023).

It has been previously shown that when using a computer, uncorrected refractive errors are likely to produce poor performance along with reduced visual comfort (Wiggins and Daum, 1991, Wiggins et al., 1992, Daum et al., 2002, Daum et al., 2004, Daum et al., 2014).

Similarly, the symptoms caused by dry eye disease have been shown to reduce workplace productivity (Yamada et al., 2012, Nichols et al., 2016, Morthen et al., 2023). It is often stated that DES can impact productivity and / or work accuracy (Charpe and Kaushik, 2009, Ranasinghe et al., 2016b, Moore et al., 2021, Kaur et al., 2022) but due to a relative scarcity of recent research, the relationship between symptoms, productivity, and work accuracy remains unclear (see Table 6.1). Given that there are approximately 5.16 billion internet users around the world (Petrosyan, 2023), and the high prevalence of DES amongst digital device users, if symptoms are associated with a reduction in productivity and / or work accuracy, it could have detrimental effects on global productivity rates, economies, and societies (Wu et al., 2021).

Cognitive load theory identifies the conscious processes of thinking as working memory (Reese et al., 2016). If an individual's working memory is overloaded, they may not be able to process anything well, thus leading to poor understanding, retention, and learning (Mestre, 2012). Cognitive load is divided into three types - intrinsic, germane, and extraneous load. Intrinsic load results from the inherent difficulty of the presented task which can be influenced by prior knowledge of the topic (Sweller and Chandler, 1994). Germane load is the work put into transferring learning to the long-term memory (Sweller et al., 1998). Extraneous load is the load generated by the way the material is presented and does not aid learning (Klepsch et al., 2017). There is some evidence to suggest that the varying level of cognitive load induced by digital tasks may affect the symptoms experienced by digital device users, potentially due to changes in blink rate; a reduction in the spontaneous eye blink rate (SEBR) and an increase in the number of incomplete blinks (Chu et al., 2014, Argilés et al., 2015, Rosenfield et al., 2015), and / or changes in pupil size (Querino et al., 2015, Miranda et al., 2018) although this relationship is not well-established.

The present study had two aims; to track the development of visuo-ocular symptoms during prolonged digital tasks (which are performed on a daily basis by many millions of individuals worldwide) and to explore the impact of higher and lower cognitive load levels on visuo-ocular symptoms, productivity, and task accuracy.

Author and year	Participants completing the study	Mean age (years)	Measures	Findings
Henning *et al*. (1997)	N = 92	Unknown	Computer operators at two work sites (n = 73, n = 19) were prompted to take three 30-seconds and one 3-minute break from computer work each hour in addition to conventional rest breaks. Some operators were asked to perform stretching exercises during the short breaks.	Productivity, eye, leg and foot comfort all improved when the short breaks included stretching exercises.
Daum *et al*. (2002)	N = 40	25.5 ± 2.9	Each VDT task involved a visual search of counties and populations, nonsense words and text editing. Time to completion and the number of errors were used as measures or productivity and a previously validated instrument was used to assess visual comfort. During four sessions, the refractive condition was manipulated to produce an array of refractive states in each eye.	Refractive error affected productivity and visual comfort.
Daum *et al*. (2004)	Unknown	19-30	Each VDT task involved a visual search of counties and populations, nonsense words	Astigmatic refractive error affected both productivity and visual comfort.

			and modified- text editing. Each participant had a 2D cylinder mis-correction.	
Wu *et al*. (2007)	N = 22	Unknown	Three, 100-minute reading trials with a different display for each trial (PDA, e-reader and a notebook computer). Visual fatigue, reading performance, and subjective satisfaction were collected at the end of each trial.	Reading speed and accuracy rate were not significantly different among the three displays.
Yamada *et al*. (2012)	N = 396	43.4 ± 13.0	Participants were classified into four groups according to the diagnostic status and subjective symptoms of dry eye: a definite dry eye group; a marginal dry eye group; a self-reported dry eye group and a control group. The impact of dry eye on work productivity was evaluated using the Japanese version of the Work Limitations Questionnaire. The cost of work productivity loss associated with dry eye and the economic benefits of providing treatment for dry eye were also assessed.	The degree of work performance loss was 5.65% in the definite dry eye group, 4.37% in the marginal dry eye group, 6.06% in the self-reported dry eye group, and 4.27% in the control group. Productivity in the self-reported dry eye group was significantly lower than that in the control group.
Daum *et al*. (2014)	N = 51	51.1 (range 40-65)	Participants used computers wearing traditional bifocal lenses (D-25) or specially designed computer eyewear, the Essilor Computer lens.	Greater visual comfort and improved work productivity for the Essilor Computer lens wearers.

Nichols *et al*. (2016)	N = 158	Unknown	Symptomatic dry eye patients naïve to prescription medication underwent standard dry eye diagnostic tests and completed Work Productivity and Activity Impairment (WPAI) and Ocular Surface Disease Index (OSDI) questionnaires.	Dry eye resulted in loss of 0.36% of work time (~5 minutes over 7 days) and ~30% impairment of workplace performance (presenteeism), work productivity, and non–job-related activities.
Morthen *et al*. (2023)	N = 71,067	18-65	Dry eye disease (DED) and unemployment, absenteeism, and 'worry about job loss' was assessed alongside work functioning, using the Work role functioning questionnaire 2.0.	DED was linked to impaired work functioning and absence, but not unemployment.

Table 6.1. Table showing previous studies which investigated the effect of refractive error / type of digital display / dry eye disease on visual comfort and / or work accuracy / productivity.

6.2 Materials and methods

6.2.1 Participants

The study adhered to the tenets of the Declaration of Helsinki of 1975 and was approved by Aston University's Health and Life Sciences Research Ethics Committee. Participants were recruited from Aston University and were enrolled following explanation of the study and after providing written consent. Sample size requirements were determined by G*Power software (version 3.1.9.7); for a 2x6 or 7 repeated measures, within factors analysis of variance (ANOVA) design; a minimum sample size of 26 / 28 participants was suggested for a 0.25 effect size, 95 % power and 5 % significance level ($\alpha = 0.05$). A greater sample size ($n = 35$) was recruited in case of any participant attrition during the study.

Participants were included in the study if they were aged 18 years or older and classified as experiencing DES, based on the computer vision syndrome questionnaire score (CVS-Q) of ≥ 6 at baseline (Seguí Mdel et al., 2015). Pregnant women, and any individuals with new or unstable general health conditions and / or medications and / or eye disease were excluded from the study.

6.2.2 Examination protocol

The study was a prospective, repeated measures study where each participant served as their own control. The study comprised of 2 visits completed on separate days at approximately the same time (mean time difference between visits = 50.5 ± 47.0 minutes). Assessments were conducted in the same room, with room temperature of 20.8 ± 1.4 °C and relative humidity of 34.2 ± 4.2 %. The same laptop (Lenovo ThinkPad L13 Gen 2) was used throughout the study (13.3" screen size, 1280 x 720 screen resolution and 250 nits screen brightness). The laptop was viewed from a 50 cm working distance (Rosenfield et al., 2009, Collier and Rosenfield, 2011, Portello et al., 2013, Chu et al., 2014) with the room lights on and participants wore their habitual refractive correction throughout (Rosenfield, 2011). Participants were instructed not to talk or look away from the screen during the task.

Figure 6.1. Photograph showing the real-world experiment setup. The laptop was viewed from a 50 cm working distance with the room lights on. Room temperature and humidity were monitored and recorded at each visit.

6.2.3 Task design

Participants were required to identify a target letter ('N') from a 5x5 grid of letters. The extraneous load was manipulated by using an adapted Eriksen Flanker task where a target letter is flanked by nontarget stimuli (Eriksen and Eriksen, 1974). Participants were presented with a Microsoft Word generated document (100% zoom level) containing 5x5 grids (each grid measured 5.95 cm x 5.95 cm) with no visible borders (see Figure 6.2). The grids contained the target letter 'N' and nontarget (distractor) letters (O, K, H, Z, W, M, V). The letter 'O' is neutral as it does not need to be actively searched and can be easily filtered out (Benoni and Tsal, 2013). The letters 'K, H, Z, W, M, V' are heterogeneous and share features with the target letter (Benoni and Tsal, 2013); this increases the task's extraneous load as the letters are not easily filtered out resulting in active searching during the task.

In both, the higher and lower cognitive load tasks, the target letter 'N' was either present or missing. In the condition where the target letter was present, both tasks had 24 nontarget

letters located within the grid. The lower cognitive load task consisted of 20 neutral ‘O’s and 4 heterogeneous letters from the selection ‘K, H, Z, W, M, V’. The higher cognitive load task consisted of 24 heterogeneous letters from the selection ‘K, H, Z, W, M, V’. In the condition where the target letter was missing, both tasks contained 25 nontarget letters. The lower cognitive load task consisted of 20 neutral ‘O’s and 5 heterogeneous letters from the selection ‘K, H, Z, W, M, V’. The higher cognitive load task consisted of 25 heterogeneous letters from the selection ‘K, H, Z, W, M, V’. A Microsoft Excel (Microsoft, Redmond, WA, USA) random number generator was used to determine the position of every letter within the grids. The option to select ‘N is missing’ was available in both versions of the task.

It is feasible that the act of scrolling on a digital device could elicit symptoms that pertain to cybersickness. Cybersickness, also known as visually induced motion sickness, induces unpleasant symptoms such as nausea, dizziness, visual fatigue, asthenopia, and headaches (Gavgani et al., 2017). Initial trialling of the tasks indicated that it took approximately twice as long to perform the higher cognitive load task compared to the lower cognitive load task therefore the grids were displayed so that a similar amount of scrolling ensued (participants only scrolled when needed) during the different cognitive load conditions (3 grids per page were displayed for the higher load task and 6 grids per page were displayed for the lower load task, see Appendix 7).

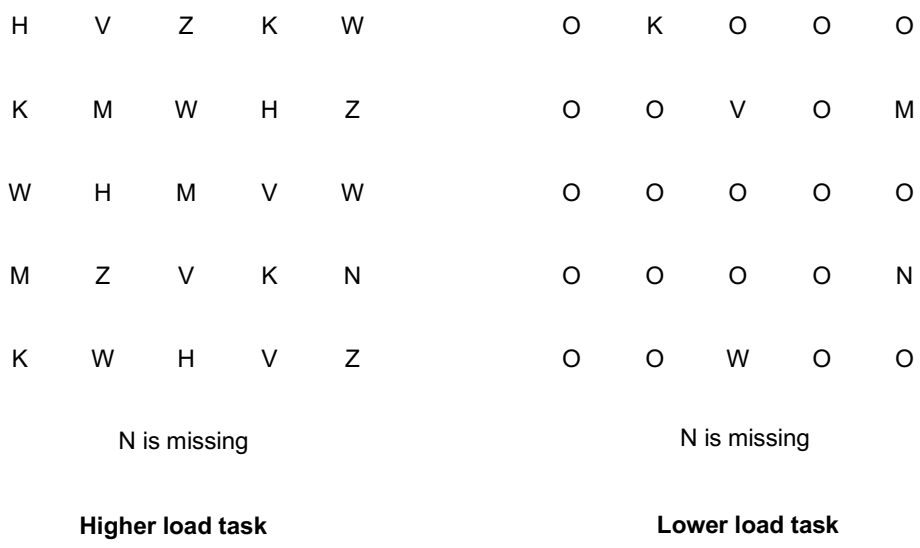


Figure 6.2. Examples of a higher cognitive load task and lower cognitive load task used during the study.

6.2.4 Participant interaction

An online random number generator was used to determine which task the participant would undertake at the first visit (where 1 = lower cognitive load task and 2 = higher cognitive load task). Participant details were confirmed including current refractive status, any known eye diseases / infections / treatment, any new and / or unstable general health conditions, and any newly prescribed medications used. Clear instructions were given to the participants – they were asked to highlight the target letter 'N' by using the Microsoft Word text highlighter tool. If they could not identify the letter 'N', they were asked to highlight 'N is missing'. If they made a mistake, they were told not to correct it and to move onto the next task. Participants rated their symptomology on a scale of 0 (no symptoms) to 10 (very severe symptoms) by using an adapted version of Hayes et al. (2007) questionnaire (Figure 6.3) (Hayes et al., 2007, Chu et al., 2011, Portello et al., 2012). At baseline, participants were asked about irritated eyes, dry eyes, eyestrain, headache, tired eyes, sensitivity to bright lights, and ocular discomfort.

After rating their baseline symptomology, the participants started the task; the task duration was 60-minutes. It was a continuous task and participants were not permitted to look away from the screen or talk during the task. At the end of every 10-minute time block, the participants rated their symptomology using a short questionnaire completed on the laptop, without resting / looking away from the screen. The participants answered the same questions that were asked at baseline, plus an additional question about blurred vision while reading from the screen. The number of completed visual tasks was also recorded. The participants returned on a different day at approximately the same time (mean time difference between visits = 50.5 $\pm$ 47.0 minutes) to undertake the second task.

Baseline Symptomology	**Intensity of the symptom. 1 = very mild, 10 = very severe**
Irritated or burning eyes	0 1 2 3 4 5 6 7 8 9 10
Dry eyes	0 1 2 3 4 5 6 7 8 9 10
Eyestrain	0 1 2 3 4 5 6 7 8 9 10
Headache	0 1 2 3 4 5 6 7 8 9 10
Tired eyes	0 1 2 3 4 5 6 7 8 9 10
Sensitivity to bright lights	0 1 2 3 4 5 6 7 8 9 10
Discomfort in your eyes	0 1 2 3 4 5 6 7 8 9 10

Symptomology recorded at the end of 10, 20, 30, 40, 50, and 60-minutes	**Intensity of the symptom. 1 = very mild, 10 = very severe**
Blurred vision while reading from the screen	0 1 2 3 4 5 6 7 8 9 10
Irritated or burning eyes	0 1 2 3 4 5 6 7 8 9 10
Dry eyes	0 1 2 3 4 5 6 7 8 9 10
Eyestrain	0 1 2 3 4 5 6 7 8 9 10
Headache	0 1 2 3 4 5 6 7 8 9 10
Tired eyes	0 1 2 3 4 5 6 7 8 9 10
Sensitivity to bright lights	0 1 2 3 4 5 6 7 8 9 10
Discomfort in your eyes	0 1 2 3 4 5 6 7 8 9 10

Figure 6.3. The adapted version of Hayes *et al*. (2007) questionnaire used in the study.

6.3 Statistical analysis

Analysis was undertaken using SPSS software version 28 (IBM Corp., New York, NY) and Microsoft Excel data analysis tools. When analysing visuo-ocular symptoms, a 2x7 (cognitive load level *versus* time) repeated-measures 2-way analysis of variance (ANOVA) within factors design was employed; cognitive load had 2 levels (higher and lower), and time had 7 levels (measured in 10-minute blocks, starting at baseline, and ending at 60 minutes). When analysing both productivity and task accuracy, a 2x6 (cognitive load level *versus* time) repeated-measures 2-way analysis of variance (ANOVA) within factors design was employed (cognitive load level and time were within subject factors). Cognitive load had 2 levels (higher and lower), and time had 6 levels (measured in 10-minute blocks, starting at 10 minutes, and ending at 60 minutes). Paired t-tests were performed to determine whether the difference between the means of the two sets of visuo-ocular symptom scores, measured at baseline (and at 10-minutes for 'blurred vision while reading from a screen') and at the end of the 60-minute task, were statistically significant in both cognitive load conditions. A Bonferroni correction was applied and the adjusted significance level (P) = 0.0031. Mauchly's Test of Sphericity was used to evaluate the assumption of sphericity. If the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied.

Productivity was calculated by counting the number of tasks completed at the end of every 10-minute interval for each (higher and lower) cognitive load level. Work accuracy was calculated by counting the number of correctly answered tasks at the end of every 10-minute interval for each (higher and lower) cognitive load level.

6.4 Results

A total of 35 adult participants (10 males and 25 females) with a mean ± standard deviation for age of 23.2 ± 4.0 years (range, 19 to 40 years) completed the study (Table 6.2). The mean ± SD baseline CVS-Q score was 9.0 ± 2.0 (range, 6.0 to 15.0).

Demographics	Value (mean ± SD)
Age (years)	23.2 ± 4.0
Male : Female	28.6 % : 71.4 %
Interval since last eye examination (months)	6.3 ± 7.8
Non-spectacle wearers	48.6 %
Spectacle and / or contact lens wearers	51.4 %
Baseline CVS-Q score	9.0 ± 2.0

Table 6.2. Demographic characteristics of the participants. Data are presented as mean ± S.D., or percentage of participants (n = 35).

6.4.1 Visuo-ocular symptoms

The mean overall symptom score at baseline was similar at 9.7 ± 10.3 and 8.4 ± 11.8 for the higher and lower cognitive load tasks respectively ($P > 0.05$).
All visuo-ocular symptom scores significantly worsened ($F = 87.783$, $p < 0.001$) with time during the 60-minute task, in both the higher and lower cognitive load conditions (Figure 6.4).

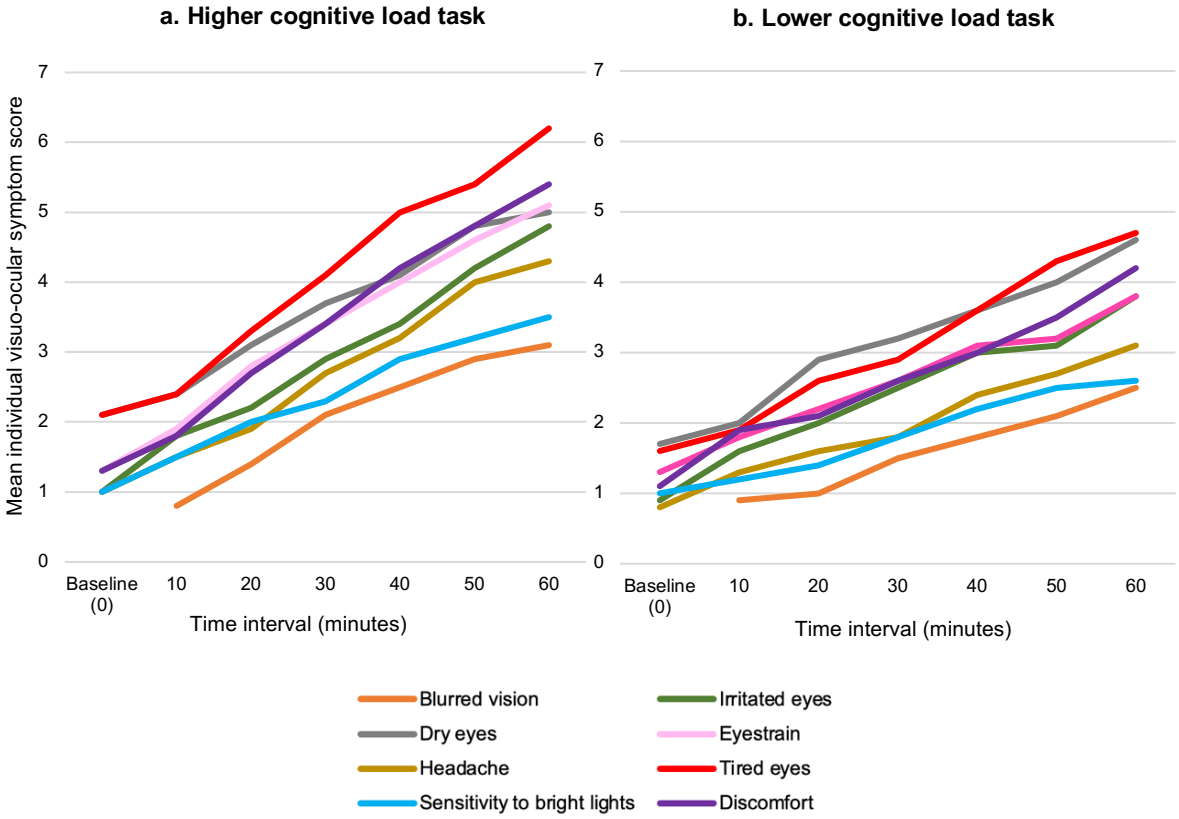


Figure 6.4. Spaghetti plots showing the mean individual visuo-ocular symptom scores for the higher (a) and lower (b) cognitive load digital tasks, over the 60-minute period for irritated eyes, dry eyes, eyestrain, headache, tired eyes, sensitivity to bright lights, ocular discomfort (all measured from baseline) and for blurred vision while reading from the screen (measured from 10-minutes).

The higher cognitive load task was associated with a higher overall level of symptoms (F = 6.559, *P* = 0.015), with the difference increasing with time (F = 7.110, p < 0.001). The mean overall symptom score at the end of the 60-minute task was 34.3 ± 16.0 and 26.7 ± 20.3 for the higher and lower cognitive load tasks respectively (*P* < 0.05; Figure 6.5).

Time interval	Mean overall symptom score for the higher cognitive load task	Mean overall symptom score for the lower cognitive load task	Significance (*p*) value
Baseline	9.7 ± 10.3	8.4 ± 11.8	0.066
10-minutes	13.5 ± 12.3	11.6 ± 14.8	0.079
20-minutes	18.0 ± 12.1	14.7 ± 15.0	0.032*
30-minutes	22.4 ± 13.3	17.3 ± 16.1	0.014

40-minutes	26.9 ± 13.6	20.9 ± 16.2	0.005
50-minutes	30.6 ± 14.3	23.4 ± 16.3	0.005
60-minutes	34.3 ± 16.0	26.7 ± 20.3	0.003

Table 6.3. Mean overall symptom scores for the higher and lower cognitive load digital tasks over the 60-minute period. Symptoms start to become significantly different between the two tasks at the 20-minute time interval.

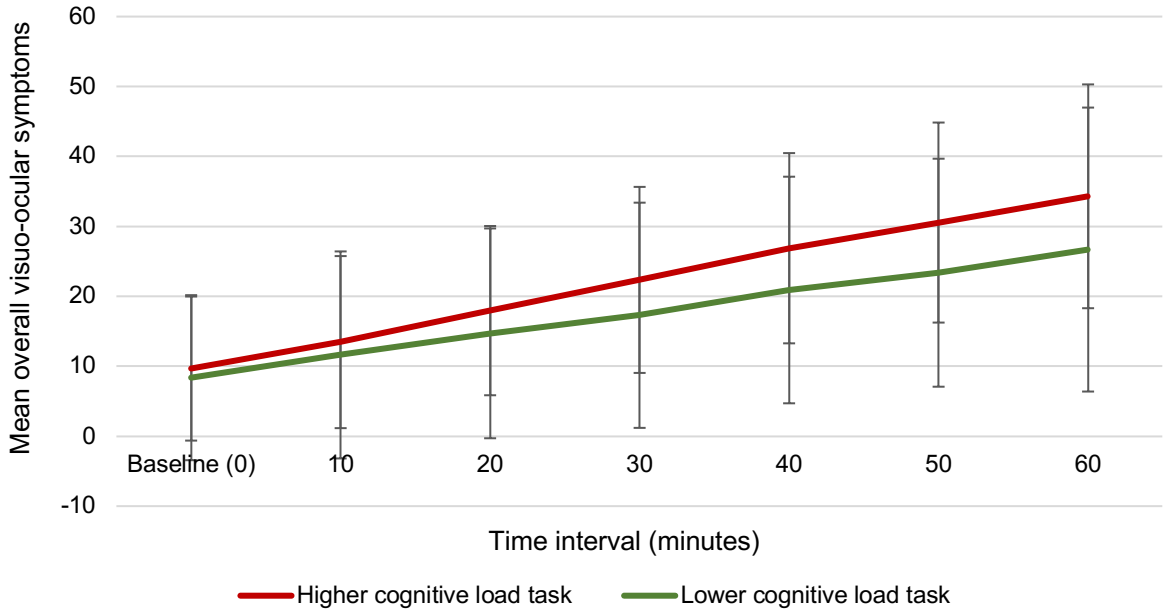


Figure 6.5. Mean overall visuo-ocular symptom score for the higher and lower cognitive load digital tasks over the 60-minute period. The error bars represent the variation in the overall visuo-ocular symptoms scores relative to the mean value.

6.4.2 Productivity

The mean total number of tasks completed was greater for the lower (1060.8 ± 296.5) than the higher (532.2 ± 123.4) cognitive load tasks ($F = 138.830$, $P < 0.001$). The number of tasks completed reduced with time ($F = 7.339$, $p < 0.001$), but in a similar way for both cognitive loads ($F = 1.795$, $P = 0.154$).

6.4.3 Task accuracy

Unlike productivity, task accuracy was not affected by the cognitive load of the task (lower demand: 98.7 ± 2.0 %; higher demand 96.2 ± 4.6 %; F = 1.729, p = 0.197) and was consistent over time (F = 1.885, p = 0.135).

6.5 Discussion

The study tracked the visuo-ocular symptoms of DES during prolonged digital tasks and explored the impact of lower and higher cognitive load levels on visuo-ocular symptoms, productivity, and task accuracy. It was shown that the impact of DES on work productivity and task accuracy over a 60-minute period is insignificant, despite a 2.5 (lower cognitive demand task) to 3.5 (higher cognitive demand task) increase in symptomology.

Several studies have shown that the amount of time spent on a digital device is a significant risk factor for DES and it is well-established that individuals with longer durations of daily use are more likely to be symptomatic (Hayes et al., 2007, Hall and Brennan-Coles, 2015, Alabdulkader, 2021, Chu et al., 2023). Previous task durations in laboratory studies have typically been in the range of 15-30 minutes (Collier and Rosenfield, 2011, Palavets and Rosenfield, 2019, Gautam, 2020, Redondo et al., 2020, Rosenfield et al., 2020, Padavettan et al., 2021, Lin et al., 2022, Talens-Estarelles et al., 2022b, Yan and Rosenfield, 2022). In this study, the mean visuo-ocular symptom score for both cognitive load conditions had significantly worsened from baseline by 10-minutes (higher cognitive load $P < 0.001$ and lower cognitive load $P < 0.001$) and the symptoms continued to increase as the task progressed. By the end of the 60-minute task, the symptoms had not plateaued. Consequently, a task duration of 15 to 60 minutes does not represent the maximum severity of DES symptoms likely to be experienced, meaning that over several hours, productivity may continue to decline, potentially lowering work output and impacting company profitability.

As the task progressed, there was a significant worsening of visuo-ocular symptoms experienced in both cognitive load conditions. However, the visuo-ocular symptoms experienced in the higher cognitive load task were significantly worse than the lower cognitive load task. There is very little research on cognitive demand and DES. It has been suggested that blinks are not executed whilst information is being processed (Wascher et al., 2015). Previous studies appear to corroborate this as higher cognitive load tasks have

been shown to reduce the mean blink rate (Rosenfield et al., 2015) and increase the percentage of incomplete blinks (Chu et al., 2014, Argilés et al., 2015). As abnormal blinking patterns are considered to be one of the main mechanisms of DES-related dry eye (Wolffsohn et al., 2023), this appears to be a credible explanation as to why dry eye symptoms worsened as the task progressed. However, it remains unclear as to why other symptoms such as eyestrain, headache and sensitivity to bright lights worsened. Neuronal injury leading to peripheral and central sensitisation through trigeminal pathways has previously been suggested (Baksh et al., 2021) but this requires further investigation.

Over the 60-minute period, participants were more productive and more accurate during the lower cognitive load task but as the task progressed, the rate of productivity decreased, but the level of task accuracy remained unchanged in both cognitive load conditions. Due to a relative scarcity of recent research, the relationship between symptoms, productivity, and task accuracy has been unclear. A 1997 study reported that productivity improved with increased ocular comfort following regular microbreaks (three 30 seconds and one 3-minute break from computer work each hour in addition to conventional rest breaks) over a 4-week treatment period, although this was not clinically significant when replicated in a larger cohort (Henning et al., 1997). A decade later, another study researched the effect of display size on visual symptoms and task accuracy. The results showed that a smaller display size resulted in significantly worse visual symptoms but reading speed and accuracy rate were similar when compared to reading from larger digital displays (Wu et al., 2007). Since these studies were published, digital technology has rapidly advanced; cathode-ray tube (CRT) monitors and lower resolution screens are no longer used, and the working environment has changed; fluorescent tube lights have been replaced by light-emitting diode (LED) lighting and air-conditioning has become a more common feature in most workplaces. The findings of this study show that worsening symptoms are associated with a reduction in productivity, but task accuracy remains unaffected; this implies that DES may not have such detrimental effects on global productivity rates, economies, and societies as previously suggested (Wu et al., 2021).

The study did not set out to manipulate the intrinsic and germane loads therefore their impact on visuo-ocular symptoms, productivity, and task accuracy remains unknown. The participants served as their own control and attended on separate days, at approximately the same time, to ensure that they had similar exposure to digital screens prior to performing the tasks. As mentioned in the task design section, it is feasible that the act of scrolling on a digital device could elicit symptoms that pertain to cybersickness, and initial trialling of the tasks indicated that it took approximately twice as long to perform the higher cognitive load

task compared to the lower cognitive load task. Therefore, the grids were displayed so that a similar amount of scrolling ensued during the different cognitive load conditions. It is likely however that the higher cognitive load task elicited greater saccadic eye movements and fixations as participants spent more time visually searching for the target letter; this may have contributed to some of the symptoms experienced such as eyestrain, ocular tiredness and/or discomfort. Despite the 60-minute task being much longer than previous studies (Collier and Rosenfield, 2011, Palavets and Rosenfield, 2019, Gautam, 2020, Redondo et al., 2020, Rosenfield et al., 2020, Padavettan et al., 2021, Lin et al., 2022, Talens-Estarelles et al., 2022b, Yan and Rosenfield, 2022), the visuo-ocular symptoms had not plateaued out by the end of the task; this raised the question - 'how much worse could the symptoms get and at what time point will they plateau out?'. Finally, as DES is based on symptoms, the purpose of the study was not to evaluate objective measures such as putative changes in the ocular surface and / or binocular vision parameters. Stopping the task to measure these parameters would have also been contrary to the objective of undertaking a continuous, uninterrupted task. However, blinking could have been monitored remotely throughout the task to explore the mechanism of the changes found in symptomology. Similarly, a formal manipulation check was not applied to each participant to assess cognitive demand and the relative demands of the different task levels; the research team had trialled the tasks internally before use to check the increased demand associated with finding the target letter in the high demand task.

6.6 Conclusion

There is very little research examining the relationship between visuo-ocular symptoms, productivity, and work accuracy. If productivity and work accuracy are affected, even by small amounts, given the billions of people around the world who are working every day on digital devices, it could have detrimental effects on global productivity rates, economies, and societies. Symptoms increased with task duration in individuals with digital eye strain, with a faster rate for more demanding tasks. This was associated with a decrease in the task completion rate (productivity), but not the work accuracy.

Chapter 7. Association between symptoms and signs of digital eye strain, dry eye disease and convergence insufficiency

7.1 Introduction

It was shown in Chapter 1 that digital eye strain (DES), dry eye disease (DED) and binocular vision anomalies (BVAs) all share similar characteristics including visual disturbance, ocular pain, ocular tiredness, ocular dryness, ocular burning, light sensitivity and headaches (TFOS, 2017, Wolffsohn et al., 2023). Over the years, studies have investigated the relationship between digital device usage and DED (Table 7.1), digital device usage and BVAs, and DED and BVAs (Table 7.2).

There are two recognised forms of DED; aqueous deficient (reduced tear secretion; this is relatively rare and related to autoimmune diseases) and evaporative (dysfunctional tear film), however individuals can have both; a combination of aqueous deficient and evaporative. Determining the major cause(s) of an individual's DED is critical in helping select the most appropriate management strategy (TFOS, 2017). Treatment for DED usually follows a stepwise approach beginning with education, dietary modifications, local environmental considerations, eyelid treatments, and then progressing onto pharmacological and non-pharmacological interventions (Shen Lee et al., 2020).

An individual with a BVA is likely to experience symptoms of eye strain during sustained near vision tasks (Rosenfield, 2011). As people are spending many hours viewing digital devices it is unknown whether eye strain symptoms are due to viewing the device or just because a sustained near vision activity is being performed. To allow people to operate devices in comfort, it is important to diagnose and then manage non-strabismic BVAs by correcting ametropia, or by using plus lenses and / or vision therapy (Hussaindeen and Murali, 2020).

The purpose of this chapter is to investigate individuals with DES, and to explore the coexistence or overlap of DED and / or BVA issues amongst DES sufferers.

Author and year	Participants completing the study	Mean age (years)	Measures	Findings
Hikichi *et al*. (1995)	N = 2,127	10 to 92	Ocular surface staining, tear film breakup time, basal tear secretion, and tear clearance.	359 participants had dry eye disease (DED). The prevalence of DED was higher in computer users.
Uchino *et al*. (2008)	N = 3,549	22 to 60	Questionnaire.	More than 4 hours of computer use was associated with an increased risk of DED.
Toomingas *et al*. (2013)	N = 1,283	36 to 50	Questionnaire.	Prolonged computer use without breaks resulted in greater ocular symptoms including dry eye.
Uchino *et al*. (2013)	N = 561	43.3 ± 9.1	Questionnaire, corneal and conjunctival staining, tear film breakup time and Schirmer's test.	More than 8 hours of computer use increased the risk of DED.
Moon *et al*. (2014)	N = 288	10 to 12	Questionnaire, best-corrected visual acuity, slit-lamp examination, and tear film breakup time.	The daily duration of smartphone use, and total daily duration of computer use were associated with increased risk of DED.
Kawashima *et al*. (2015)	N = 369	44.4 ± 8.8	Questionnaire, corneal and conjunctival staining, tear film breakup time and Schirmer's test.	60 % of computer users were diagnosed with DED.
Moon *et al*. (2016)	N = 916	7 to 12	Questionnaire, slit lamp examination and tear film breakup time.	Smartphone use in children was strongly associated with paediatric DED.
Hanyuda *et al*. (2020)	N = 102,582	40 to 74	Questionnaire.	Prolonged sedentary behaviours and computer use

				had a higher prevalence of DED.
Inomata *et al*. (2020)	N = 21, 394	27.9 ± 12.6	Questionnaire.	More than 8 hours of computer use was associated with DED.
Wang *et al*. (2021)	N = 322	41.0 ± 22.0	Lifestyle factor questionnaire, OSDI questionnaire, DEQ-5 questionnaire, tear meniscus height, non-invasive tear film breakup time, tear film lipid layer, tear osmolarity, ocular surface staining and infrared meibography.	Increased screen exposure time and reduced caffeine consumption were modifiable lifestyle factors associated with higher odds of DED.
Wolffsohn *et al*. (2021)	N = 1,125	33.0 ± 21.0	Demographic and lifestyle factor questionnaire, DEQ-5 questionnaire, conjunctival hyperaemia, infrared meibography, tear meniscus height, non-invasive breakup time, and lipid layer grade.	Digital screen time per day was a risk factor for DED.
Talens-Estarelles *et al*. (2022c)	N = 851	Unknown	Online survey: CVS-Q, OSDI, DEQ-5, 8-item Contact Lens Dry Eye Questionnaire, and dry eye risk factors from the TFOS Dry Eye Workshop II.	Several dry eye-related risk factors and health conditions are associated with suffering from digital eye strain (DES).
Albalawi *et al*. (2023)	N = 1,593	18 to 25	Questionnaire.	More than 6 hours of computer use was associated with more severe DED symptoms.

Table 7.1. Table showing previous studies which have investigated the relationship between digital device usage and symptoms and / or signs of dry eye disease.

Author and year	Participants completing the study	Mean age (years)	Measures	Findings
Rueff *et al*. (2014)	N = 95	51.3 ± 13.6	Ocular Surface Disease Index (OSDI) and Convergence Insufficiency Symptom Survey (CISS) questionnaires.	Scores on the OSDI and the CISS were positively correlated.
Kaido *et al*. (2017)	N = 12	49.6 ± 18.3	Verbal rating scale of dry eye symptoms, TBUT, assessment of keratoconjunctival epithelial damage, Schirmer test, visual acuity, blink frequency, refractive error, range of accommodation, and accommodative micro-fluctuations.	Tear film instability is associated with deterioration of functional visual acuity, accommodative micro-fluctuations, and dry eye symptoms.
Golebiowski *et al*. (2020)	N = 12	18 to 23	Reading task on a smartphone for 60-minutes. The following measures were taken before and after the reading task: eye strain and ocular surface symptoms, non-invasive tear break-up time, lipid layer appearance, tear meniscus height, horizontal fixation disparity, binocular accommodative facility. Spontaneous blink rate and amplitude were counted every 10 minutes.	Extended use of smartphones appears to have implications for ocular surface health and binocular function.
Mohan *et al*. (2021)	N = 46	14.5 ± 2.0	Screen time, CISS, near exophoria, negative fusional vergence, negative relative	Online classes longer than 4 hours were more detrimental to abnormal binocular

			accommodation, and accommodation amplitude.	vergence and accommodation parameters.
Yammouni and Evans, 2021	N = 107	20 to 40	CVS-Q and mSANDE, ocular pathology, dry eye assessment, refractive error, visual acuity, ocular motility, ocular alignment, vergence, and accommodation measures.	Digital eye strain (DES) is multi-factorial in nature. +0.75D lenses may be beneficial for many people suffering the symptoms of DES, especially if in the age range from 20 to 40 years.
Auffret *et al*. (2022)	N = 52	Unknown	Ocular discomfort questionnaire, refraction, phoria, near point of accommodation and convergence, fusional vergence, and binocular amplitude facility.	Binocular balance is disturbed by intensive and chronic use of screens.
Gupta *et al*. (2022)	N = 13	53.5 ± 16.7	OSDI questionnaire, visual acuity, and clinical exam findings (not stated).	Correction of non-strabismic binocular visual dysfunction in patients with multifactorial dry eye disease, along with traditional dry eye treatment modalities, results in a statistically significant decrease in OSDI scores.
Gorimanipalli *et al*. (2023)	N = 32	32 (19 to 39)	Demographic information, Schirmer 1 and 2, TBUT, OSDI, near point of accommodation, near point of convergence, positive and negative fusional vergences, accommodative and vergence facility.	There is a significant overlap between symptoms of dry eye disease and non-strabismic binocular vision anomalies.

Table 7.2. Table showing previous studies which have investigated the relationship between digital device usage and binocular vision anomalies and dry eye disease and binocular vision anomalies.

7.2 Methods

7.2.1 Participants

The study adhered to the tenets of the Declaration of Helsinki of 1975 and was approved by Aston University's Health and Life Sciences Research Ethics Committee (reference number HLS1822). Participants were recruited from both Aston University and the general public and were enrolled following explanation of the study and after providing written consent. Participants were eligible for inclusion in the study if they were aged 18 years or older and classified as experiencing DES, based on the Computer Vision Syndrome Questionnaire (CVS-Q) score of ≥ 6 at baseline (Seguí Mdel et al., 2015). Pregnant women, and any individuals with new or unstable general health conditions and / or medications and / or eye disease were excluded from the study. A total of 41 participants were recruited. 26 were female and the average age was 31.1 ± 11.3 years. Their spherical equivalent (SE) prescriptions ranged from +3.00 D to -9.25 D (average -1.79 ± 2.89 D).

7.2.2 Examination protocol

The study was a prospective, repeated measures study where each participant served as their own control. The study comprised of 3 visits completed on separate days and each participant attended their visits at approximately the same time (mean time difference between visits = 1.1 ± 1.9 hours). Assessments were conducted in the same room, with room temperature of 20.9 ± 1.2 °C and relative humidity of 39.1 ± 8.4 %.

At the start of each visit, participants were asked to complete the Ocular Surface Disease Index questionnaire (OSDI), the Computer Vision Syndrome Questionnaire (CVS-Q) and the revised Convergence Insufficiency Symptom Survey questionnaire (CISS). Participants were also asked about their daily screen time (this was calculated as the sum of desktop, laptop, tablet / iPad, smartphone, smartwatch, e-reader and television usage per day). The monocular (right eye) best corrected distance visual acuity, best corrected near visual acuity, stereopsis, fixation disparity, ocular alignment, binocular accommodative facility, and near point of convergence were all measured. The order of the measurements was chosen to minimise the effects of fatigue. The Oculus Keratograph 5M topographer (K5M; Oculus Optikgerate, Wetzlar, Germany) was used to examine the ocular surface and tear film. Measurements were taken from the right eye only. The testing procedures were based on the guidelines of the TFOS DEWS II Diagnostic Methodology report (Wolffsohn et al., 2017)

and were performed in the following order (least invasive to most invasive) - spontaneous blinking pattern, tear meniscus height (TMH), bulbar and limbal redness, lipid layer thickness (LLT), non-invasive breakup time (NIKBUT), corneal and conjunctival staining, lid wiper epitheliopathy (LWE) and upper and lower lid meibography. Slit lamp biomicroscopy was used to evaluate meibomian gland function. Chapter 2 discusses in detail how these tests were conducted.

7.3 Statistical analysis

Sample size requirements were based on the primary outcome measure of a change in symptomology determined by G*Power software (version 3.1.9.7); a minimum sample size of 20 participants was suggested with 0.25 effect size, 80 % power and 5 % significance level ($\alpha = 0.05$).

The data were analysed with SPSS (Version 25, SPSS Inc, Chicago, II, USA). Data that were found to be normally distributed (OSDI score, CVS-Q score, CISS score, total number of blinks per minute, number of complete blinks per minute and tear meniscus height; $p > 0.05$) had parametric, repeated-measure (ANOVA) and Pearson correlation tests applied. Metrics where the data were not normally distributed (best corrected distance visual acuity, best corrected near visual acuity, stereopsis, fixation disparity, ocular alignment, binocular accommodative facility, and near point of convergence (break and recovery values), number of incomplete blinks per minute, bulbar and limbal redness, non-invasive breakup time, corneal and conjunctival staining, lid wiper epitheliopathy, upper and lower lid meibography and lower lid meibomian gland expressibility; $p < 0.05$), had non-parametric, repeated-measures Friedman and Spearman rank correlation tests applied. Values of $p < 0.05$ were taken as statistically significant.

7.4 Results

7.4.1 Subjective Measures

7.4.1.1 Ocular Surface Disease Index questionnaire

The average OSDI score after the three visits was 29.9 ± 15.8 and there was no difference in the OSDI score between the visits ($p = 0.308$). 8 participants had an OSDI score of 0 to 12 (normal ocular surface). 33 out of the 41 participants had an average OSDI score ≥ 13 (indicative of symptomatic ocular surface disease); 3 participants had an OSDI score of 13 to

22 (mild dry eye disease), 13 participants had an OSDI score 23 to 32 (moderate dry eye disease) and 17 participants had an OSDI score of 33 to 100 (severe dry eye disease); see figure 7.1. For the rest of this chapter, the 8 participants with an OSDI score < 13 will be referred to as the 'normal OSDI group' and the 33 participants with an OSDI score ≥ 13 will be referred to as the 'symptomatic OSDI group'. The normal OSDI group had an average OSDI score of 10.7 ± 7.9 whereas the symptomatic OSDI group had a significantly higher ($p = 0.001$) average OSDI score of 34.5 ± 12.8.

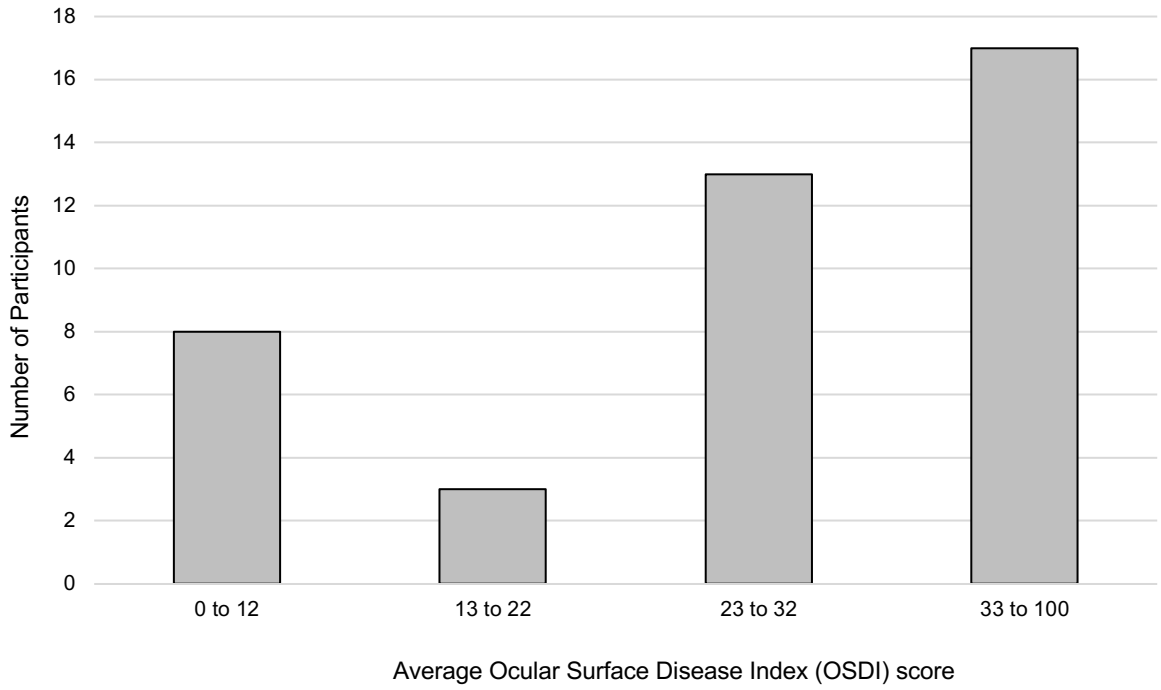


Figure 7.1. Bar chart showing the number of participants against their average Ocular Surface Disease Index (OSDI) score after the three visits.

The OSDI questionnaire consists of 12 questions. The breakdown of the percentage of participants who experienced each symptom / environmental trigger / vision-related impact on the quality of life is shown in figure 7.2. In the normal OSDI group, the most experienced symptom was light sensitivity (75 %). In the symptomatic OSDI group, the most experienced symptom was painful / sore eyes (87.9 %).

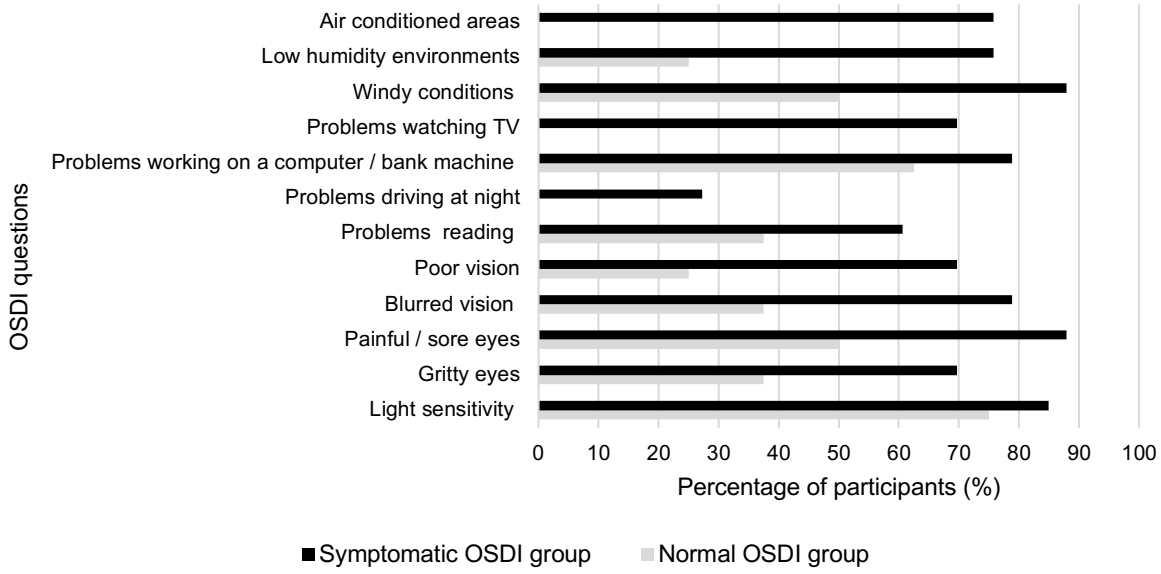


Figure 7.2. Chart showing the percentage of participants who experienced each symptom / environmental trigger / vision-related impact on the quality of life in the OSDI questionnaire.

7.4.1.2 Computer Vision Syndrome Questionnaire

The CVS-Q questionnaire consists of 16 questions. The breakdown of the percentage of participants who experienced each symptom in the CVS-Q questionnaire is shown in figure 7.3. In the normal OSDI group, the most experienced symptoms were headache, eye redness and ocular itching (75 % respectively). In the symptomatic OSDI group, the most experienced symptom was ocular dryness (93.9 %).

The average CVS-Q score after the three visits was 10.9 ± 3.7 and there was no difference in the CVS-Q score between the visits ($p = 0.114$). The normal OSDI group had an average CVS-Q score of 7.4 ± 1.4 whereas the symptomatic OSDI group had a significantly higher ($p < 0.001$) average CVS-Q score of 11.7 ± 3.8.

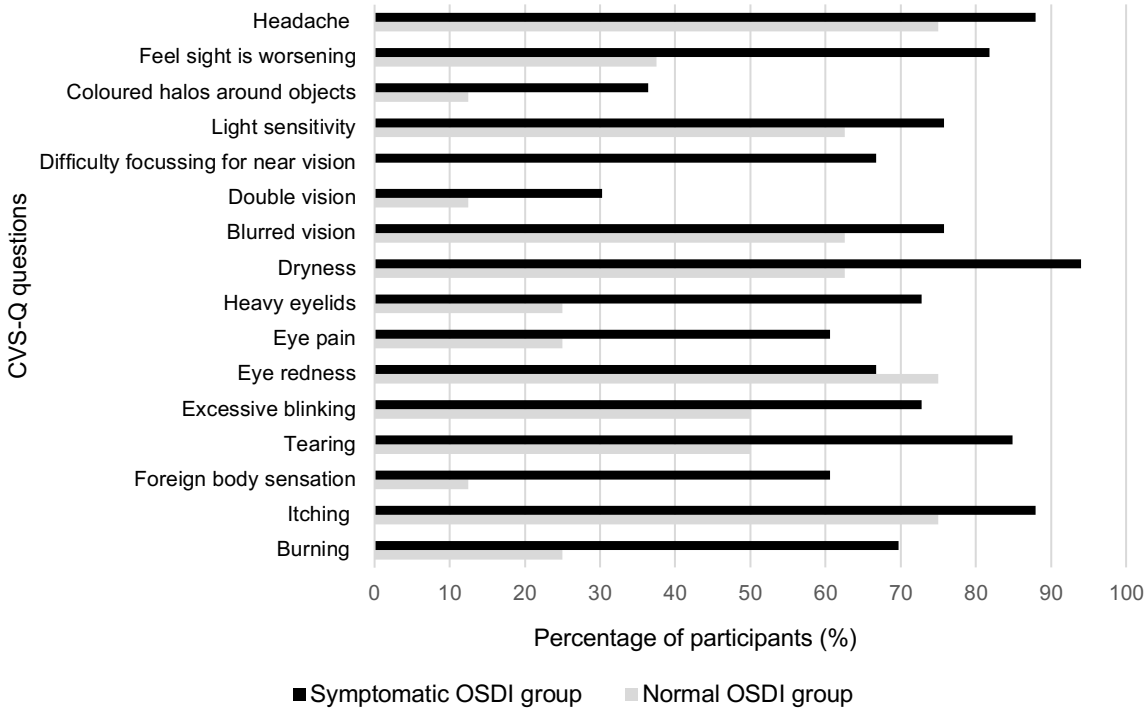


Figure 7.3. Chart showing the percentage of participants who experienced each symptom in the Computer Vision Syndrome (CVS-Q) questionnaire.

As shown in figure 7.4, there was a moderately positive correlation between the average OSDI and CVS-Q scores ($r = 0.616$, $p < 0.001$).

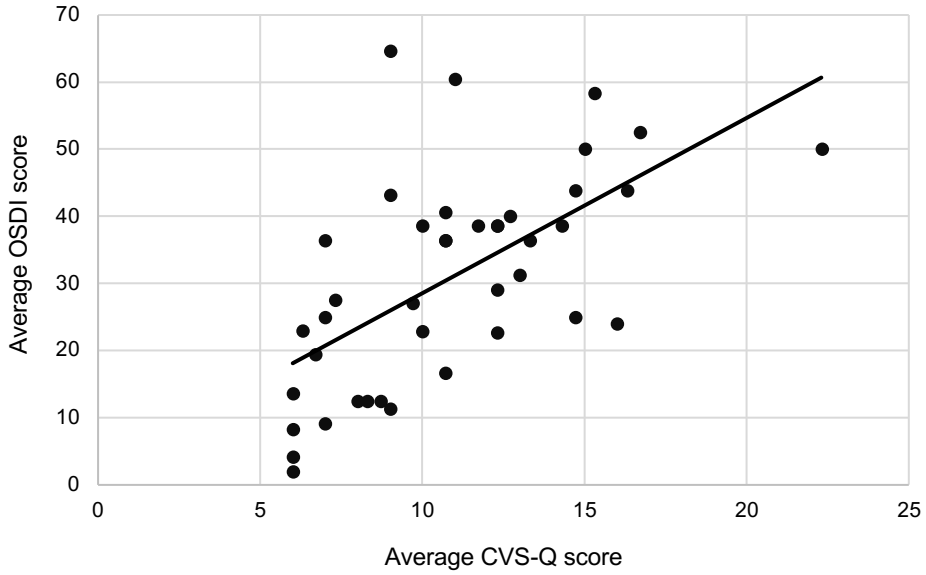


Figure 7.4. Scatter plot and its corresponding linear regression line showing the relationship between the average OSDI scores and the average CVS-Q scores for all participants.

7.4.1.3 The revised Convergence Insufficiency Symptom Survey questionnaire

The revised Convergence Insufficiency Symptom Survey (CISS) questionnaire consists of 15 questions. A score ≥ 21 is indicative of symptomatic convergence insufficiency. The average CISS score after the three visits was 19.1 ± 7.8 and there was no difference in the CISS score between the visits ($p = 0.054$). The normal OSDI group had an average CISS score of 12.3 ± 6.2 whereas the symptomatic OSDI group had a significantly higher ($p = 0.019$) average CISS score of 20.4 ± 7.3.

As shown in figure 7.5, there was a moderately positive correlation between the average OSDI and CISS scores ($r = 0.519$, $p = 0.0005$).

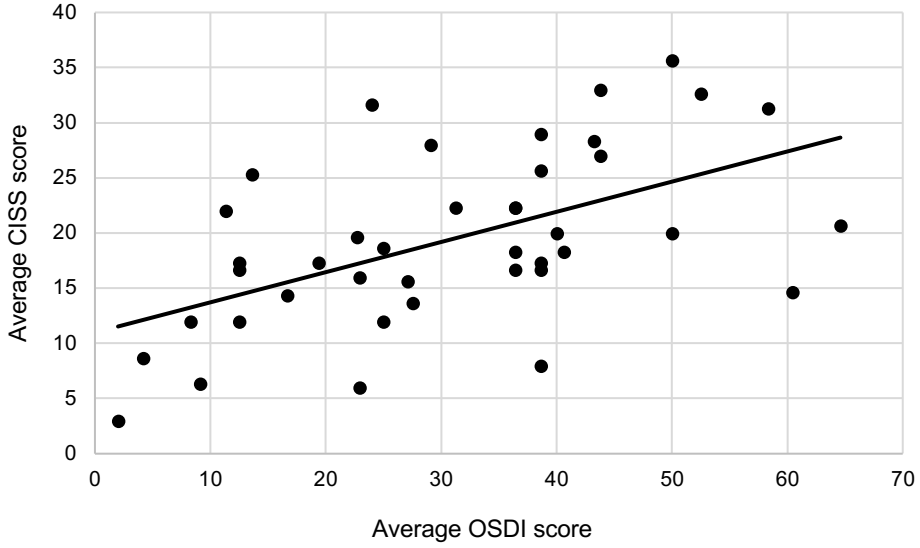


Figure 7.5. Scatter plot and its corresponding linear regression line showing the relationship between the average CISS scores and the average OSDI scores for all participants.

As shown in figure 7.6, there was a moderately positive correlation between the average CISS and CVS-Q scores ($r = 0.635$, $p < 0.001$).

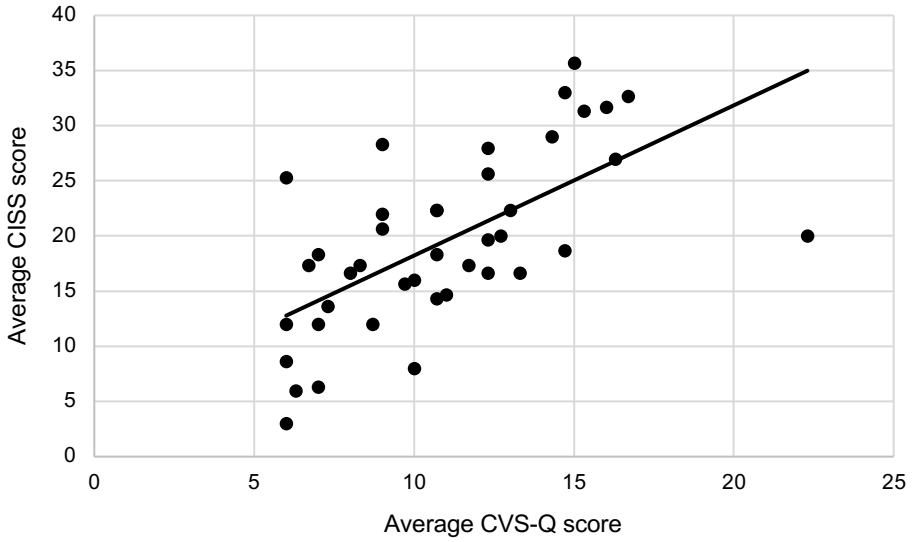


Figure 7.6. Scatter plot and its corresponding linear regression line showing the relationship between the average CISS scores and the average CVS-Q scores for all participants.

7.4.1.4 Screen time

The overall average daily screen time was 16.7 ± 6.1 hours. There was no difference in the average daily screen time between the normal OSDI group and the symptomatic OSDI group (p = 0.491).

Measured parameter	**Normal OSDI group.** **(N = 8).** **Mean ± SD**	**Symptomatic OSDI group.** **(N = 33).** **Mean ± SD**	**Paired t-test *p* value**
OSDI score	10.7 ± 7.9	34.5 ± 12.8	0.001
CVS-Q score	7.4 ± 1.4	11.7 ± 3.8	< 0.001
CISS score	12.3 ± 6.2	20.4 ± 7.3	0.019
Daily screen time	16.4 ± 4.5	17.0 ± 7.7	0.491

Table 7.3. Table showing the mean ± SD values for the normal OSDI group and symptomatic OSDI group against the measured parameters and the paired t-test p values.

Measured parameter	Mean ± SD Visit 1	Mean ± SD Visit 2	Mean ± SD Visit 3	*p* value
OSDI score	30.9 ± 15.8	30.0 ± 16.0	29.0 ± 16.0	0.308
CVS-Q score	11.2 ± 3.8	10.5 ± 3.9	10.9 ± 4.0	0.114
CISS score	19.8 ± 7.7	18.9 ± 7.9	18.6 ± 8.0	0.054

Table 7.4. Table showing the overall (N = 41) mean ± SD values after visits 1, 2 and 3 against the measured parameters and the ANOVA p values.

7.4.2 Objective Measures

7.4.2.1 Visual and Binocular Vision Measures

Tables 7.5 and 7.6 show the visual and binocular vision measures after the three visits along with the statistical results of the comparison.

Measured parameter	Normal OSDI group. (N = 8). Mean ± SD	Symptomatic OSDI group. (N = 33). Mean ± SD	Paired t-test *p* value
Best corrected distance visual acuity (right eye)	0.0 ± 0.0	0.1 ± 0.2	0.020
Best corrected near visual acuity	0.3 ± 0.0	0.3 ± 0.0	p > 0.999
Stereopsis (arc seconds)	40.0 ± 40.0	60.0 ± 40.0	0.500
Fixation disparity (ΔD)	0.0 ± 0.0	0.2 ± 0.5	0.351
Ocular alignment (ΔD)	0.8 ± 0.4	0.9 ± 0.6	0.598
Binocular accommodative facility (cycles per minute)	7.6 ± 3.0	7.6 ± 3.7	0.126
Near point of convergence – break (cm)	3.5 ± 3.8	4.0 ± 5.3	0.371

Near point of convergence - recovery (cm)	9.5 ± 1.7	11.6 ± 5.4	0.667

Table 7.5. Table showing the mean ± SD values for the normal OSDI group and symptomatic OSDI group against the measured parameters and the paired t-test p values.

Measured parameter	**Mean ± SD Visit 1**	**Mean ± SD Visit 2**	**Mean ± SD Visit 3**	***p* value**
Best corrected distance visual acuity (right eye)	0.1 ± 0.2	0.1 ± 0.2	0.1 ± 0.2	p > 0.999
Best corrected near visual acuity	0.3 ± 0.0	0.3 ± 0.0	0.3 ± 0.0	p > 0.999
Stereopsis (arc seconds)	50 ± 40	50 ± 40	50 ± 40	p > 0.999
Fixation disparity (ΔD)	0.2 ± 0.5	0.2 ± 0.5	0.2 ± 0.5	p > 0.999
Ocular alignment (ΔD)	0.9 ± 0.6	0.9 ± 0.5	0.9 ± 0.6	p > 0.999
Binocular accommodative facility (cycles per minute)	7.7 ± 3.7	7.4 ± 3.6	7.6 ± 3.6	0.006
Near point of convergence – break (cm)	3.9 ± 5.0	4.1 ± 5.1	4.1 ± 5.0	p > 0.999
Near point of convergence - recovery (cm)	11.2 ± 5.0	11.2 ± 5.0	11.0 ± 4.8	p > 0.999

Table 7.6. Table showing the overall (N = 41) mean ± SD values after visits 1, 2 and 3 against the measured parameters and the ANOVA / Friedman p values.

7.4.2.2 Tear Film Related Metrics

The average total number of blinks per minute (spontaneous eye blink rate) was 18.3 ± 7.7. The average number of complete blinks per minute was 13.7 ± 8.2 and the average number

of incomplete blinks per minute was 4.6 ± 5.3. As shown in table 7.7, there was no difference between the normal OSDI group and the symptomatic OSDI group for any of the three blinking parameters (p = 0.302, p = 0.485 and p = 0.703 respectively) and as shown in table 7.8, there was no difference in any of the three blinking parameters between the visits (p = 0.072, p = 0.140 and p = 0.317 respectively).

The average tear meniscus height (TMH) was 0.3 ± 0.06. There was no difference between the normal OSDI group and the symptomatic OSDI group (p = 0.581) and there was no difference in the TMH between the visits (p = 0.089).

The average bulbar redness was 0.8 ± 0.4. The average limbal redness was 0.6 ± 0.3. There was no difference between the normal OSDI group and the symptomatic OSDI group for both bulbar and limbal redness (p = 0.642 and p = 0.07 respectively) and there was no difference in the bulbar redness and limbal redness between the visits (p = 0.459 and p = 0.879 respectively).

The average lipid layer thickness (LLT) in both groups was graded as a wave lipid layer, see figure 7.7.

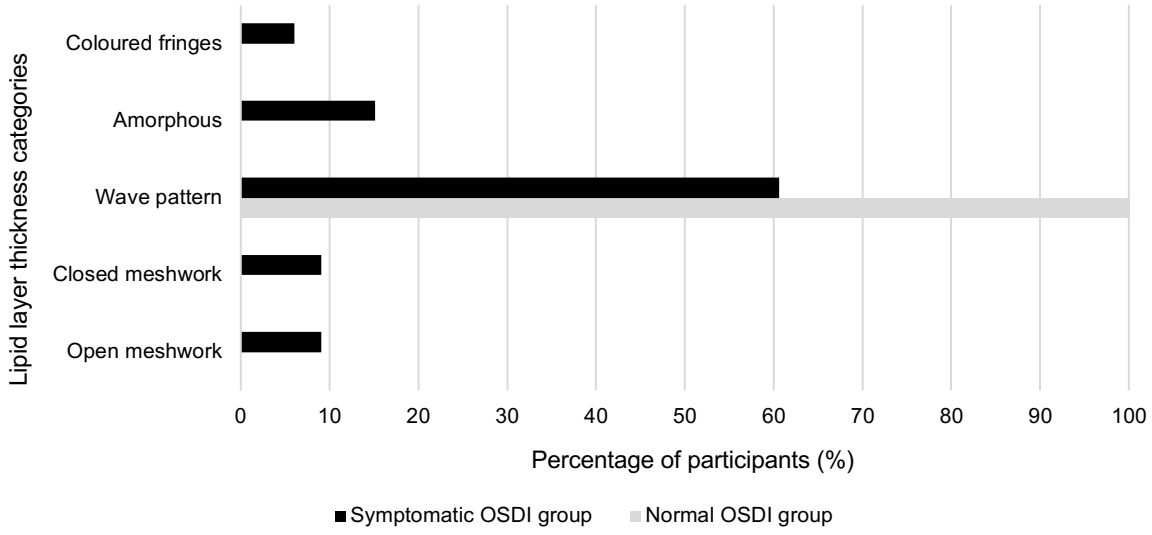


Figure 7.7. Chart showing the percentage of participants in each group and their average lipid layer thickness.

The average non-invasive breakup time (NIKBUT) was 10.8 ± 5.0 seconds. There was no difference between the normal OSDI group and the symptomatic OSDI group (p = 0.864) however there was a difference in the NIKBUT between the visits (p = 0.025).

The average corneal staining was 0.2 ± 0.4. The average conjunctival staining was 0.3 ± 0.4. There was no difference between the normal OSDI group and the symptomatic OSDI group for both corneal and conjunctival staining (p = 0.563 and p =0.275 respectively) and there was no difference in the corneal staining and conjunctival staining between the visits (p = 0.252 and p = 0.572 respectively).

The average lid wiper epitheliopathy (LWE) was 1.3 ± 0.04. The normal OSDI group had an average LWE of 0.5 ± 1.0 whereas the symptomatic OSDI group had a significantly higher (p = 0.037) average LWE of 1.5 ± 1.0. There was no difference in the LWE between the visits (p = 0.331).

The average upper lid meibography drop-out grade was 1.1 ± 0.8. The average lower lid meibography grade was 0.5 ± 0.5. There was no difference between the normal OSDI group and the symptomatic OSDI group for both upper and lower lid meibography (p = 1.0 and p = 0.862 respectively) and there was no difference in the upper lid meibography and lower lid meibography between the visits (p = 0.196 and p = 0.584 respectively).

7.4.2.3 Slit lamp biomicroscopy

The average number of expressed lower lid meibomian glands was 3.6 ± 1.2; this translates to grade 1 on the Pflugfelder *et al*. (1998) grading system (3 to 4 glands were expressible). There was no difference between the normal OSDI group and the symptomatic OSDI group (p > 0.999) but in the normal OSDI group meibum appeared clear, whereas in the symptomatic OSDI group meibum appeared like a cloudy liquid.

Measured parameter	**Normal OSDI group.** **(N = 8).** **Mean ± SD**	**Symptomatic OSDI group.** **(N = 33).** **Mean ± SD**	**Paired t-test *p* value**
Total number of blinks per minute	16.5 ± 5.3	18.8 ± 8.2	0.302
Complete blinks per minute	11.5 ± 5.9	14.2 ± 8.6	0.485

Incomplete blinks per minute	5.0 ± 5.5	4.5 ± 5.3	0.703
Tear meniscus height	0.3 ± 0.04	0.3 ± 0.07	0.581
Bulbar redness	0.8 ± 0.3	0.8 ± 0.4	0.642
Limbal redness	0.7 ± 0.4	0.6 ± 0.3	0.070
Lipid layer thickness	Wave	Wave	-
Non-invasive breakup time	10.6 ± 4.5	11.0 ± 5.4	0.864
Corneal staining	0.2 ± 0.3	0.2 ± 0.5	0.563
Conjunctival staining	0.2 ± 0.3	0.3 ± 0.5	0.275
Lid wiper epitheliopathy	0.5 ± 1.0	1.5 ± 1.0	0.037
Upper lid meibography	1.0 ± 0.6	1.1 ± 0.8	> 0.999
Lower lid meibography	0.4 ± 0.4	0.5 ± 0.6	0.862
Lower lid meibomian gland expressibility	4.0 ± 0.5	3.5 ± 1.3	> 0.999

Table 7.7. Table showing the mean ± SD values for the normal OSDI group and symptomatic OSDI group against the measured parameters and the paired t-test p values.

Measured parameter	**Mean ± SD Visit 1**	**Mean ± SD Visit 2**	**Mean ± SD Visit 3**	***p* value**
Total number of blinks per minute	18.2 ± 9.3	16.2 ± 8.6	16.1 ± 8.6	0.072
Complete blinks per minute	14.5 ± 9.4	13.6 ± 8.1	13.0 ± 7.0	0.140

Incomplete blinks per minute	5.4 ± 6.5	4.2 ± 4.8	4.2 ± 4.5	0.317
Tear meniscus height	0.3 ± 0.0	0.3 ± 0.1	0.3 ± 0.1	0.089
Bulbar redness	0.8 ± 0.3	0.8 ± 0.3	0.8 ± 0.4	0.459
Limbal redness	0.6 ± 0.3	0.6 ± 0.3	0.6 ± 0.3	0.879
Lipid layer thickness	Wave	Wave	Wave	-
Non-invasive breakup time	10.0 ± 4.6	11.1 ± 4.9	11.8 ± 5.5	0.025
Corneal staining	0.3 ± 0.6	0.1 ± 0.3	0.2 ± 0.4	0.252
Conjunctival staining	0.3 ± 0.4	0.3 ± 0.3	0.3 ± 0.3	0.572
Lid wiper epitheliopathy	1.3 ± 1.0	1.2 ± 1.0	1.3 ± 1.1	0.331
Upper lid meibography	1.1 ± 0.8	1.1 ± 0.8	1.1 ± 0.8	0.196
Lower lid meibography	0.5 ± 0.6	0.5 ± 0.5	0.5 ± 0.5	0.584
Lower lid meibomian gland expressibility	3.7 ± 1.2	3.6 ± 1.2	3.6 ± 1.2	p > 0.999

Table 7.8. Table showing the overall (N = 41) mean ± SD values after visits 1, 2 and 3 against the measured parameters and the ANOVA / Friedman p values.

7.5 Discussion

The purpose of the current study was to determine if individuals with DES also experience symptoms and / or signs of DED and / or BVAs. A robust, repeated measures study was performed. The most commonly used DES questionnaire (CVS-Q), dry eye questionnaire

(OSDI) and convergence insufficiency questionnaire (CISS) was utilised to assess symptoms. In addition, the average daily screen time was recorded and objective measures of monocular (right eye) best corrected distance visual acuity, best corrected near visual acuity, stereopsis, fixation disparity, ocular alignment, binocular accommodative facility, near point of convergence, spontaneous blinking pattern, tear meniscus height (TMH), bulbar and limbal redness, lipid layer thickness (LLT), non-invasive breakup time (NIKBUT), corneal and conjunctival staining, lid wiper epitheliopathy (LWE), upper and lower lid meibography and meibomian gland function were assessed.

All participants were classified as experiencing DES, based on a CVS-Q score of ≥ 6 (Seguí Mdel et al., 2015) at recruitment. 33 out of the 41 participants (80.5 %) had an average OSDI score ≥ 13 (indicative of symptomatic ocular surface disease); these individuals were grouped into the symptomatic OSDI group. The remaining 8 participants (19.5 %) had a normal OSDI score (< 12); they did not meet the TFOS DEWS II criteria for DED and were placed into the normal OSDI group. The self-reported daily screen time was considerably higher than the typical values reported in other studies, leading the thesis author to suspect that participants may have overestimated the time spent on digital devices. However, there was no difference in self-reported daily screen time between the two groups. Notably, the symptomatic OSDI group had significantly higher CVS-Q and CISS scores compared to the normal OSDI group. The results revealed a moderately positive correlation between the CVS-Q and CISS, CVS-Q and OSDI, and CISS and OSDI scores

The symptomatic OSDI group had a reduced best corrected distance visual acuity in the right eye, however, this was not clinically meaningful and may have been an artifact as there was no difference in the best corrected near visual acuity, stereopsis, fixation disparity, ocular alignment, binocular accommodative facility, and near point of convergence (break and recovery values) between the two groups and all participants had normal binocular vision findings for their respective ages. There was no difference in any of the visual and binocular vision measures between the visits apart from binocular accommodative facility which may have been due to examiner (time taken to mechanically flip the lenses) and participant (time taken to name the target) error rather than actual accommodative issues.

The normal spontaneous eye blink rate (sEBR) is between 12 and 22 blinks per minute (Tsubota and Nakamori, 1993, Doughty, 2001, Argilés et al., 2015). In the present study, the average sEBR was within normal limits (18.3 ± 7.7) and there was no difference between the two groups. Previous studies have demonstrated that the sEBR reduces during screen usage (Patel et al., 1991, Tsubota and Nakamori, 1993). As there was no difference in the

daily screen time between the two groups, this could be the reason why no difference in the sEBR was observed between the two groups.
It is generally accepted that in normal eyes, the TMH is between 0.2 and 0.4 mm, whereas in aqueous deficient dry eyes, the TMH is < 0.2 mm (Doughty et al., 2002, TFOS, 2017). In the present study, the average TMH was within normal limits (0.3 ± 0.06; ruling out aqueous deficient DED) and there was no difference between the two groups. Bulbar and limbal redness is a common clinical sign in many ocular conditions including DED (Macchi et al., 2018). In the present study, the average bulbar redness (0.8 ± 0.4) and the average limbal redness (0.6 ± 0.4) were less than grade 1 on the JENVIS grading scale and there was no difference between the two groups.

The NIKBUT is a measure of the time between a blink and the disruption of the Placido rings (projected from the K5M) reflected in the tear film. A NIKBUT value ≤ 10 seconds indicates DED (TFOS, 2017). NIKBUT is correlated with the severity of DED, especially in the aqueous deficient type (TFOS, 2017). The average NIKBUT measurement was within normal limits at 10.8 ± 5.0 seconds. Although the average NIKBUT varied across visits (p = 0.025), likely due to natural fluctuations in the daily environment or factors such as changes in humidity, no significant difference was observed between the two groups (p = 0.864); this implies that the tear film breakdown may primarily occur when using digital devices.

In DED, it is common to observe corneal and/or conjunctival staining. Ocular surface damage in the central cornea exacerbates dry eye symptoms (Iii et al., 2006). The average corneal staining (0.2 ± 0.4) and the average conjunctival staining (0.3 ± 0.4) were less than grade 0.5 on the JENVIS grading scale. There was no difference between the two groups for both corneal and conjunctival staining.

The average upper lid meibography was graded as 1.1 ± 0.7 and the average lower lid meibography was graded as 0.5 ± 0.5. There was no difference between the two groups. Gland expressibility is scored according to the number of the 8 glands from which a fluid secretion can be expressed (Tomlinson et al., 2011). The average expression was grade 1 (which corresponds to 3 to 4 expressible glands) and there was no difference between the two groups. A normal tear film exhibits at least a closed-meshwork lipid layer pattern (Craig and Downie, 2019). The average LLT in both groups was graded as a wave lipid layer pattern; this is related to a LLT between 50 to 80 nm which is acceptable.
The present study did show significant differences between the two groups in LWE and meibum secretions, where both measures were worse in the symptomatic OSDI group.

LWE involves inflammation resulting from increased friction between the lid wiper of the superior eyelid and the anterior ocular surface. LWE is associated with an unstable tear film and may be exacerbated by factors such as abnormal blinking patterns, adverse environmental influences and sub-clinical inflammation (Efron et al., 2016). The normal OSDI group had an average LWE of 0.5 ± 1.0 (classified as grade 1 LWE) whereas the symptomatic OSDI group had a significantly higher average LWE of 1.5 ± 1.0 (classified as grade 2 LWE); this is a moderate level of LWE and it is indicative of moderate inflammation which may contribute to symptoms of dryness, grittiness, ocular soreness, and burning (Korb et al., 2004).

Normal meibum quality of each gland should form an oil-dome with a clear liquid secretion upon expression (Korb and Blackie, 2008, Blackie and Korb, 2009). In the normal OSDI group, secreted meibum appeared clear whereas in the symptomatic OSDI group meibum had a cloudy liquid appearance; this is characteristic of mild meibomian gland dysfunction (MGD) which may be accompanied by symptoms of ocular surface irritation, visual fluctuation, and potential ocular surface compromise (Nichols et al., 2011, Tomlinson et al., 2011).

In the present study, DES sufferers with an OSDI score < 12 had a normal CISS score, normal binocular vision, and a normal ocular surface and tear film. DES sufferers with an OSDI score ≥ 13 also had a normal CISS score and normal binocular vision but had a significantly worse CVS-Q score and demonstrated signs of mild MGD and moderate LWE, indicative of evaporative DED. Referring to the author's systematic review of artificial tears (Appendix 8), individuals with evaporative DED benefit from artificial tears with liposomes, especially of higher concentration (Semp et al., 2023). As the meibomian glands are the main source of lipids for the tear film, lid hygiene with lid warming followed by moderate to firm massage and expression of MG secretions would also be prudent (Nichols et al., 2011).

The present study would have benefitted by having a larger number of participants and a wider age range. Unfortunately, participant enrolment proved to be more difficult than expected. Secondly, a 6-month follow-up (Craig et al., 2021) after implementing treatment for evaporative DED would have been useful to determine if DED treatment helps alleviate / reduce DES symptoms.

7.6 Conclusion

The present study is believed to be the first of its type which has demonstrated a moderately positive relationship between all three questionnaires: the CVS-Q, OSDI and CISS. These findings indicate that in clinical practice, patients reporting DES symptoms are also likely to be symptomatic of DED and / or a BVA so it would be prudent for Optometrists to perform a thorough dry eye and binocular vision assessment as part of the eye examination.
It was also shown that evaporative DED appears to worsen symptoms therefore appropriate treatment such as artificial tears with liposomes and lid hygiene with lid warming followed by moderate to firm massage and expression of MG secretions should be implemented to help alleviate symptoms (Nichols et al., 2011, TFOS, 2017, Semp et al., 2023).

When assessing DES symptomology, it is important to identify whether symptoms are specific to digital device usage, ocular surface disease, performing a sustained near-vision task, or a combination of some or all of these variables. As demonstrated in the present study, the CVS-Q failed to differentiate symptoms specific to when individuals are performing a digital task, hence a refined questionnaire is needed. The author of the thesis aims to address this by designing and developing a new DES questionnaire (Chapter 8).

Chapter 8. Developing a new digital eye strain questionnaire

8.1 Introduction

Digital eye strain (DES) is defined as “the development or exacerbation of recurrent ocular symptoms and/or signs related specifically to digital device screen viewing” (Wolffsohn et al., 2023). The increase in digital device usage over the years (Chapter 1, section 1.2.2) has led to a rise in the number of people who suffer with DES. In 2024, the prevalence of DES amongst working adults in the UK & Ireland was recorded as 62.6 % (Moore et al., 2024). The global prevalence of DES is estimated to be 70.7 % (Wolffsohn et al., 2023) but it has been shown to be higher in some populations (e.g. 97.3 % in Saudia Arabia (Altalhi et al., 2020)).

As DES is diagnosed through symptoms, the use of questionnaires is crucial when assessing and diagnosing the condition. Over the years a variety of questionnaires have been used to identify people who suffer with DES and to grade the severity of symptoms (Table 8.1). In the experimental chapters of the thesis, DES / visual fatigue (VF) symptomology was assessed by using the Computer Vision Syndrome Questionnaire (CVS-Q; Chapters 4, 5 & 7) and the adapted version of Hayes *et al*. (2007) questionnaire (Chapter 6). However, the literature review (Chapter 1) and previous experimental chapters highlighted that the current questionnaires used to identify and grade DES have not been as robustly developed as they should be and do not differentiate symptoms specific to when individuals are performing a digital task (Wolffsohn et al., 2023). Given the global prevalence of DES, it would be reasonable to develop a validated questionnaire that can be used globally, and which is relevant to different populations whilst assessing symptoms in real time.

Developing a validated questionnaire can take months / years as many different stages are involved (Gehlbach et al., 2010, Artino et al., 2014). The first 4 stages have been completed. The remaining stages are due to be completed beyond the scope of the thesis.

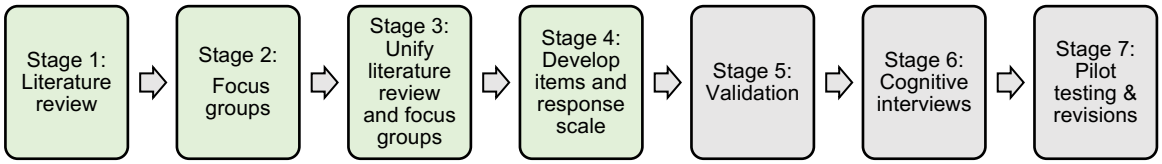


Figure 8.1. Flowchart showing the different stages of developing a new, validated questionnaire. The author of the thesis has completed the first 4 stages.

8.2 Literature review

The first stage in developing a new DES questionnaire is to conduct a comprehensive literature review of previous and current computer vision syndrome (CVS) / DES / VF papers; this enables existing questionnaires (and their respective items and survey response scales) to be identified and the range of questions they use to define DES (Cook and Beckman, 2006).

A search was made of the Web of Science databases (Clarivate Analytics, Philadelphia, USA) which includes the Science Citation Index Expanded covering over 9200 of the world's most impactful journals from 1900 to the present day along with PubMed (including MEDLINE) from its inception. The systematic review was conducted in the format prescribed by PRISMA (Page et al., 2021). A search for "digital eye strain*", "computer vision syndrome*", "visual fatigue*" AND "questionnaire" or "survey" were screened by the author of the thesis. Studies were eligible to be accepted if they were in full paper form (not abstracts or book chapters), written in English and reported the use of a questionnaire to identify individuals with DES.

The search resulted in an initial 442 papers, but only 36 papers were included in the review (Figure 8.2). Out of the 36 papers, 18 different questionnaires were identified; these are summarised in table 8.1.

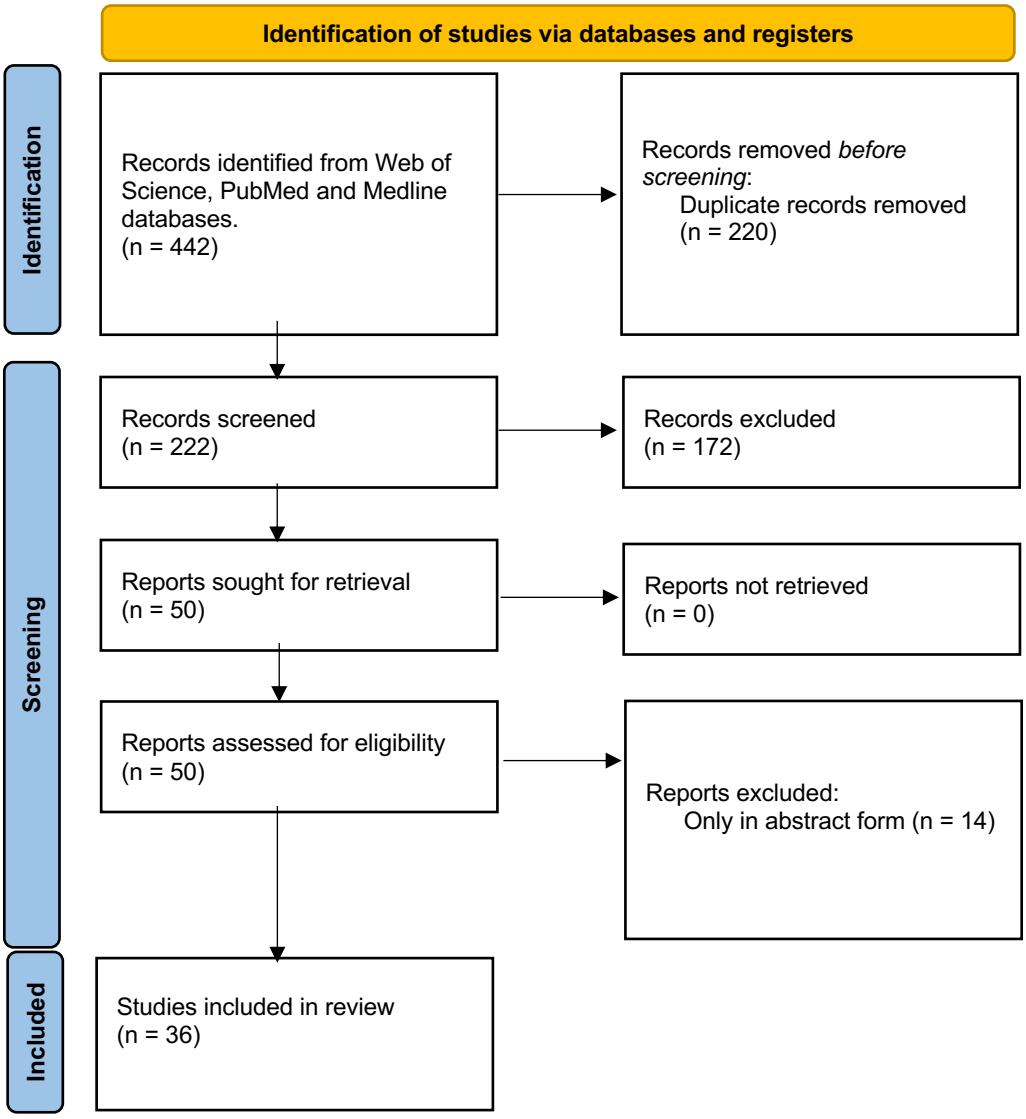


Figure 8.2. PRISMA 2020 flow diagram of the systematic review search results.

Notes: PRISMA figure adapted from Liberati A, Altman D, Tetzlaff J, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. Journal of clinical epidemiology. 2009;62(10). Creative Commons. (Liberati et al., 2009).

	Symptom	**Questionnaire**					
		Takahashi *et al*. (1993)	**Mocci *et al*. (2001)**	**Sheedy *et al*. (2003)**	**Ames *et al*. (2005)**	**Hayes *et al*. (2007) '21- item questionnaire'**	**Kuze *et al*. (2008)**
1	Blurred vision at near / difficulty focusing at near	Graded on a scale of 0-6				Graded on a scale of 0-6	Graded on a scale of 0-7
2	Blurred vision at intermediate					Graded on a scale of 0-6	
3	Blurred vision at distance	Graded on a scale of 0-6				Graded on a scale of 0-6	Graded on a scale of 0-7
4	Blurred vision / difficulties in seeing	Graded on a scale of 0-6 (asked three times)	Graded on a scale of 0-3	Graded on a scale of 0-100	Graded on a scale of 0-6		Graded on a scale of 0-7
5	Difficulty in vision post-screen use / issues with colours	Graded on a scale of 0-6					
6	Sight worsening						
7	Difficulty in refocusing from one distance to another	Graded on a scale of 0-6			Graded on a scale of 0-6	Graded on a scale of 0-6	
8	Double vision		Graded on a scale of 0-3	Graded on a scale of 0-100			Graded on a scale of 0-7
9	Crossing your eyes						
10	Eye strain			Graded on a scale of 0-100	Graded on a scale of 0-6	Graded on a scale of 0-6	Graded on a scale of 0-7

11	Dry eyes	Graded on a scale of 0-6		Graded on a scale of 0-100	Graded on a scale of 0-6	Graded on a scale of 0-6	Graded on a scale of 0-7
12	Irritated / burning / stinging eyes	Graded on a scale of 0-6 (asked twice)		Graded on a scale of 0-100 (asked twice)	Graded on a scale of 0-6 (asked twice)	Graded on a scale of 0-6	Graded on a scale of 0-7
13	Eye fatigue / tired eyes	Graded on a scale of 0-6			Graded on a scale of 0-6 (asked twice)	Graded on a scale of 0-6	
14	Eyes hurt / eye pain	Graded on a scale of 0-6	Graded on a scale of 0-3	Graded on a scale of 0-100	Graded on a scale of 0-6	Graded on a scale of 0-6	
15	Photophobia	Graded on a scale of 0-6 (asked twice)				Graded on a scale of 0-6	
16	Headache	Graded on a scale of 0-6		Graded on a scale of 0-100		Graded on a scale of 0-6	Graded on a scale of 0-7
17	Strange feeling around the eyes / pressure	Graded on a scale of 0-6					
18	Numbness						
19	Dizziness						Graded on a scale of 0-7
20	Excessive blinking	Graded on a scale of 0-6	Graded on a scale of 0-3				
21	Eyelid twitching	Graded on a scale of 0-6					
22	Heavy eyes / eyelids		Graded on a scale of 0-3				Graded on a scale of 0-7
23	Watery eyes / tearing	Graded on a scale of 0-6		Graded on a scale of 0-100	Graded on a scale of 0-6		Graded on a scale of 0-7
24	Eye redness	Graded on a scale of 0-6					

25	Itchy eyes		Graded on a scale of 0-3				
26	Foreign body sensation						
27	Coloured halos around objects						
28	Neck pain					Graded on a scale of 0-6	Graded on a scale of 0-7
29	Shoulder pain					Graded on a scale of 0-6	Graded on a scale of 0-7
30	Elbow/Forearm pain					Graded on a scale of 0-6	
31	Hand/wrist pain					Graded on a scale of 0-6	
32	Finger(s) pain					Graded on a scale of 0-6	
33	Upper back pain					Graded on a scale of 0-6	
34	Lower back pain					Graded on a scale of 0-6	
35	Thighs/knees pain					Graded on a scale of 0-6	
36	Lower leg pain					Graded on a scale of 0-6	
37	Ankle/foot pain					Graded on a scale of 0-6	
38	Insomnia						
39	Depression						
40	Pain, stiffness, numbness or tingling in the neck / shoulder / back						

41	Nausea / sickness						Graded on a scale of 0-7
42	Inability to hold objects well						
43	Difficulty to write using a pen						
44	Frequency of symptoms						
45	Severity of symptoms						

Table 1 continued…

	Symptom	**Questionnaire**					
		Benedetto *et al*. (2013) 'Visual fatigue scale'	**Reddy *et al*. (2013)**	**González-Pérez *et al*. (2014) 'CVSS17'**	**Seguí Mdel *et al*. (2015) 'CVS-Q'**	**Ranasinghe *et al*. (2016)**	**Mowatt *et al*. (2018)**
1	Blurred vision at near / difficulty focusing at near				Frequency and intensity	0 (mild-moderate) or 1 (severe)	
2	Blurred vision at intermediate			No / yes (a little) / yes (a lot)			
3	Blurred vision at distance					0 (mild-moderate) or 1 (severe)	
4	Blurred vision / difficulties in seeing	10-point Likert scale	Circle if relevant	Yes (a lot) / yes (a little) / never	Frequency and intensity		None / mild / moderate / severe

5	Difficulty in vision post-screen use / issues with colours					0 (mild-moderate) or 1 (severe)	
6	Sight worsening				Frequency and intensity		
7	Difficulty in refocusing from one distance to another						
8	Double vision		Circle if relevant	Yes / no	Frequency and intensity	0 (mild-moderate) or 1 (severe)	None / mild / moderate / severe
9	Crossing your eyes			Never / rarely, frequently or constantly			
10	Eye strain		Circle if relevant	False / quite true / totally true			None / mild / moderate / severe
11	Dry eyes		Circle if relevant	False / quite true / totally true	Frequency and intensity	0 (mild-moderate) or 1 (severe)	None / mild / moderate / severe
12	Irritated / burning / stinging eyes			Constantly / frequently / rarely or never	Frequency and intensity	0 (mild-moderate) or 1 (severe)	None / mild / moderate / severe
13	Eye fatigue / tired eyes	10-point Likert scale	Circle if relevant	Never / yes (for a short amount of time) / yes (for a long amount of time)			
14	Eyes hurt / eye pain		Circle if relevant	Constantly / frequently / rarely / never	Frequency and intensity	0 (mild-moderate) or 1 (severe)	
15	Photophobia			Never / hardly ever / repeatedly (asked twice)	Frequency and intensity		

16	Headache	10-point Likert scale	Circle if relevant		Frequency and intensity	0 (mild-moderate) or 1 (severe)	None / mild / moderate / severe
17	Strange feeling around the eyes / pressure	10-point Likert scale					
18	Numbness	10-point Likert scale					
19	Dizziness	10-point Likert scale					
20	Excessive blinking			Never / rarely / frequently / constantly	Frequency and intensity		
21	Eyelid twitching					0 (mild-moderate) or 1 (severe)	
22	Heavy eyes / eyelids			False / quite true / totally true (asked twice)	Frequency and intensity		
23	Watery eyes / tearing		Circle if relevant	Never / a little / a lot	Frequency and intensity	0 (mild-moderate) or 1 (severe)	
24	Eye redness		Circle if relevant	Never / a little / a lot	Frequency and intensity	0 (mild-moderate) or 1 (severe)	
25	Itchy eyes			Constantly / frequently / rarely / never	Frequency and intensity		
26	Foreign body sensation				Frequency and intensity		
27	Coloured halos around objects				Frequency and intensity		
28	Neck pain		Circle if relevant				None / mild / moderate / severe
29	Shoulder pain		Circle if relevant				None / mild / moderate / severe
30	Elbow/Forearm pain						

31	Hand/wrist pain						
32	Finger(s) pain						
33	Upper back pain		Circle if relevant				
34	Lower back pain		Circle if relevant				
35	Thighs/knees pain						
36	Lower leg pain						
37	Ankle/foot pain						
38	Insomnia						
39	Depression						
40	Pain, stiffness, numbness or tingling in the neck / shoulder / back						
41	Nausea / sickness						
42	Inability to hold objects well						
43	Difficulty to write using a pen						
44	Frequency of symptoms						
45	Severity of symptoms						

Table 1 continued…

	Symptom	**Questionnaire**					
		Ahuja *et al*. (2021)	**AlDarrab *et al*. (2021)**	**Iqbal *et al*. (2021) 'CVS-F3'**	**Das *et al*. (2022)**	**Sharbini *et al*. (2022) 'DESRIL-27'**	**Mylona *et al*. (2022) 'DESQ'**
1	Blurred vision at near / difficulty focusing at near	Tick if applicable		Tick if applicable			
2	Blurred vision at intermediate						
3	Blurred vision at distance						
4	Blurred vision / difficulties in seeing	Tick if applicable	Graded on a scale of 0-3	Tick if applicable	Graded on a scale of 0-5	Symptom severity scale: Frequency and intensity	Yes / no
5	Difficulty in vision post-screen use / issues with colours	Clear / blurry / hazy		Tick if applicable			
6	Sight worsening					Symptom severity scale: Frequency and intensity	
7	Difficulty in refocusing from one distance to another			Tick if applicable		Symptom severity scale: Frequency and intensity	
8	Double vision	Tick if applicable	Graded on a scale of 0-3	Tick if applicable		Symptom severity scale: Frequency and intensity	Yes / no
9	Crossing your eyes						
10	Eye strain		Graded on a scale of 0-3	Tick if applicable			Yes / no

11	Dry eyes	Often / sometimes / never	Graded on a scale of 0-3	Tick if applicable	Graded on a scale of 0-5		Yes / no
12	Irritated / burning / stinging eyes	Tick if applicable	Graded on a scale of 0-3		Graded on a scale of 0-5	Symptom severity scale: Frequency and intensity	Yes / no
13	Eye fatigue / tired eyes				Graded on a scale of 0-5		
14	Eyes hurt / eye pain	Tick if applicable			Graded on a scale of 0-5	Symptom severity scale: Frequency and intensity	
15	Photophobia					Symptom severity scale: Frequency and intensity	Yes / no
16	Headache		Graded on a scale of 0-3		Graded on a scale of 0-5	Symptom severity scale: Frequency and intensity	Yes / no
17	Strange feeling around the eyes / pressure						
18	Numbness						
19	Dizziness						
20	Excessive blinking	Tick if applicable				Symptom severity scale: Frequency and intensity	
21	Eyelid twitching						
22	Heavy eyes / eyelids	Tick if applicable					
23	Watery eyes / tearing	Tick if applicable			Graded on a scale of 0-5	Symptom severity scale: Frequency and intensity	Yes / no
24	Eye redness	Tick if applicable		Tick if applicable	Graded on a scale of 0-5		Yes / no
25	Itchy eyes	Tick if applicable			Graded on a scale of 0-5	Symptom severity scale: Frequency and intensity	

26	Foreign body sensation	Tick if applicable				Symptom severity scale: Frequency and intensity	Yes / no
27	Coloured halos around objects					Symptom severity scale: Frequency and intensity	Yes / no
28	Neck pain		Graded on a scale of 0-3				Yes / no
29	Shoulder pain		Graded on a scale of 0-3				Yes / no
30	Elbow/Forearm pain						
31	Hand/wrist pain			Tick if applicable			
32	Finger(s) pain			Tick if applicable			
33	Upper back pain						
34	Lower back pain						
35	Thighs/knees pain						
36	Lower leg pain						
37	Ankle/foot pain						
38	Insomnia			Tick if applicable			
39	Depression			Tick if applicable			
40	Pain, stiffness, numbness or tingling in the neck / shoulder / back			Tick if applicable		Symptom severity scale: Frequency and intensity	
41	Nausea / sickness						
42	Inability to hold objects well			Tick if applicable			
43	Difficulty to write using a pen			Tick if applicable			

44	Frequency of symptoms	Never / 1 to < 5 times a week / 2 to > 5 times a week					
45	Severity of symptoms	Mild / disturbs work / severe to stop work and take rests					

Table 8.1. Table showing the different questionnaires (and their respective items and survey response scales) used in various digital eye strain / computer vision syndrome / visual fatigue studies. Note: Sharbini et al. (2022) 'DESRIL-27' also has a risk level scale regarding work environment and ergonomic factors in digital screen users consisting of 11 items asking about workplace environment, device or equipment, work hours / breaks / exercises and workstation set up and ergonomics.

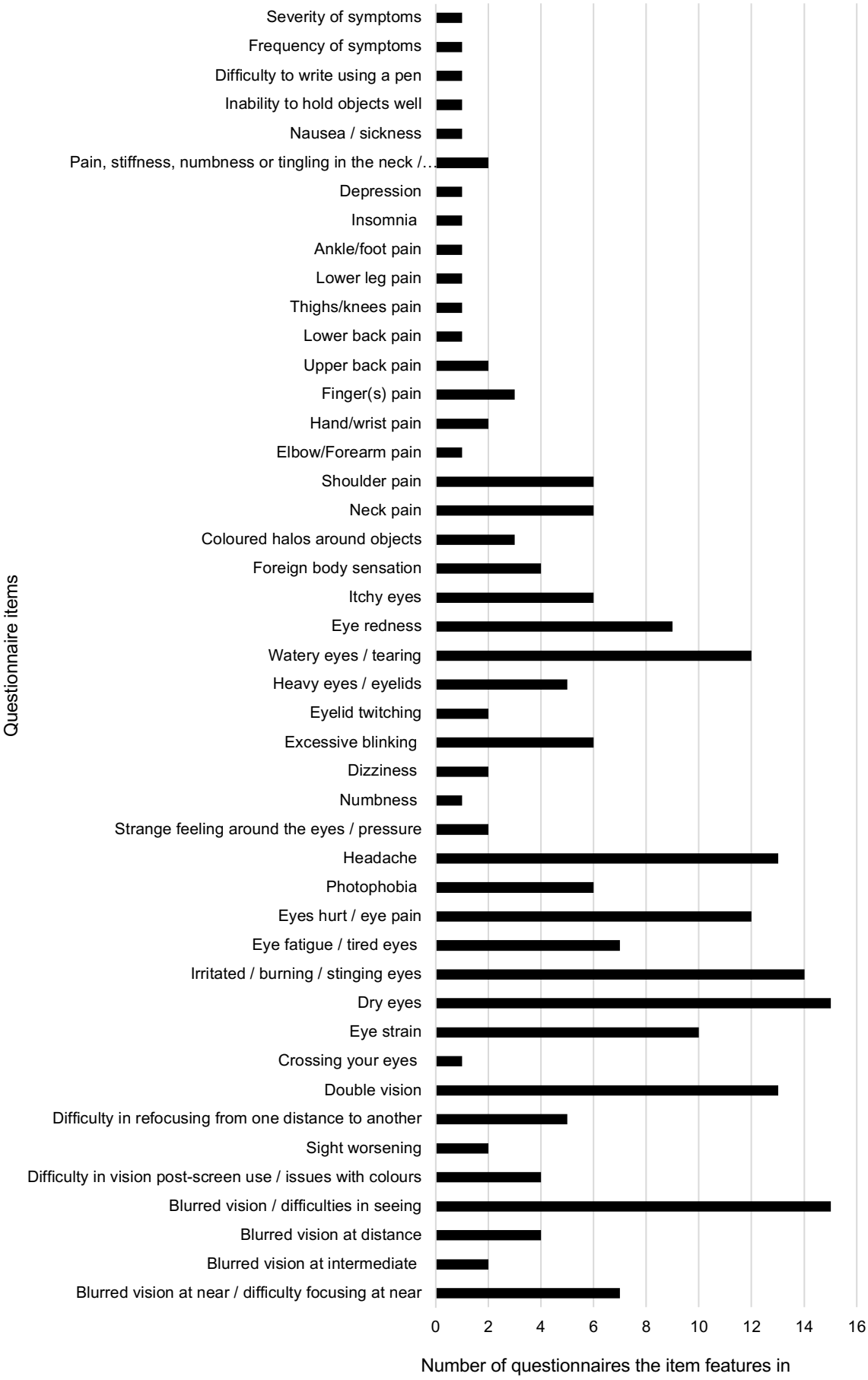

Severity of symptoms
Frequency of symptoms
Difficulty to write using a pen
Inability to hold objects well
Nausea / sickness
Pain, stiffness, numbness or tingling in the neck /…
Depression
Insomnia
Ankle/foot pain
Lower leg pain
Thighs/knees pain
Lower back pain
Upper back pain
Finger(s) pain
Hand/wrist pain
Elbow/Forearm pain
Shoulder pain
Neck pain
Coloured halos around objects
Foreign body sensation
Itchy eyes
Eye redness
Watery eyes / tearing
Heavy eyes / eyelids
Eyelid twitching
Excessive blinking
Dizziness
Numbness
Strange feeling around the eyes / pressure
Headache
Photophobia
Eyes hurt / eye pain
Eye fatigue / tired eyes
Irritated / burning / stinging eyes
Dry eyes
Eye strain
Crossing your eyes
Double vision
Difficulty in refocusing from one distance to another
Sight worsening
Difficulty in vision post-screen use / issues with colours
Blurred vision / difficulties in seeing
Blurred vision at distance
Blurred vision at intermediate
Blurred vision at near / difficulty focusing at near
Questionnaire items
0
2
4
6
8
10
12
14
16
Number of questionnaires the item features in

Figure 8.3. Chart showing the 45 items identified from the 18 different questionnaires against the number of questionnaires the items feature in.

The papers indicated that the questionnaires were self-administered. A total of 45 items and 2 different response scales (Likert and dichotomous scales) were identified. The most frequently asked items were blurred vision, dry eyes, irritated / burning / stinging eyes, eye redness, double vision, headache, eyes hurt / eye pain, eye strain and watery eyes / excessive tearing (Figure 8.3); this corresponds with the findings of the literature review performed by Seguí *et al*. (2015). However, some ambiguity was observed in the item terminology used, for example, 'irritated / burning / stinging eyes' can be interpreted differently and may cause confusion when being evaluated.

Over two-thirds of the identified CVS / DES / VF questionnaires employed Likert scales to obtain responses (Table 8.1). Likert scales present a list of categorised response options in an ordered fashion, with the aim of reflecting an underlying continuum of an attribute (Likert, 1932). For example, in the questionnaire used by Das *et al*. (2022), participants were required to indicate the amount of agreement with a presented item on a scale of 0 to 5, where '0' indicated no agreement and '5' indicated a very strong agreement. This is a simple approach which is easily interpretable, either in the form of a mean score of all items or by the total questionnaire score (Likert, 1932). However, mean scores may not fairly characterise the data as responses are placed in a ranked order and no inference can be made as to the true difference between each of the items. Therefore the responses from Likert scales must be statistically analysed in a way that allows an interval scale to be estimated from ordinal scales, so that an actual measure of the true attribute can be obtained (Massof and Rubin, 2001). Over the years, there has been a dispute over the use of parametric versus non-parametric methods for the analysis of Likert scales however parametric tests are advised in questionnaires with high response rates ($n > 15$) as more in-depth analyses of the data can be undertaken (Mircioiu and Atkinson, 2017).

A dichotomous scale is a rating scale that only offers respondents two options such as 'yes' or 'no' and was used in 4 of the identified questionnaires (Reddy et al., 2013, Ranasinghe et al., 2016a, Iqbal et al., 2021, Mylona et al., 2022). The simplistic nature of dichotomous scales means they do not capture respondents' true feelings and can result in survey bias. The Chi-Square test is used to statistically analyse the relationship between the two variables (Haq and Nazir, 2016).

The most commonly used DES questionnaire, the CVS-Q, uses a combination of Likert (frequency: never / occasionally / often or always) and dichotomous (intensity: moderate / intense) rating scales. Rasch analysis then transforms the ordinal scores to the logit scale and thus to an interval-level measurement, resulting in a single symptom severity score (Seguí Mdel et al., 2015). With Rasch analysis, both respondents and items are scaled on the same continuum and items are differentiated from each other by 'difficulty', whereas in Likert scaling all items have the same weight in the summating procedure (van Alphen et al., 1994).

Although this goes beyond the scope of the thesis, the author intends to employ Rasch analysis to calibrate the new DES questionnaire. Rasch analysis will enable the author to assess the validity and reliability of the items within the questionnaire, ensuring that they are appropriately scaled and that each item contributes meaningfully to the overall measurement of DES. This process will involve evaluating the item difficulty, person ability, and the overall fit of the data to the Rasch model. Although a detailed examination of Rasch analysis falls outside the immediate focus of the current thesis, the intention is to use this approach in future work to refine the new DES questionnaire further, providing stronger psychometric evidence for its use in clinical and research settings.

8.3 Focus groups

The second stage in developing a new DES questionnaire is to conduct multiple focus groups to learn how the symptomatic population (individuals with a CVS-Q score ≥ 6) conceptualise and describe DES. A focus group usually consists of 5 to 10 participants (Ratnapalan and Hilliard, 2002) and are conducted either in-person, online, or a combination of both. With little to no prompting, participants talk about DES in their own words. The facilitator then asks more focused questions to assess if the participants agree with the way DES has been characterised in the literature. The procedure is repeated until the facilitator no longer hears new information about how the participants conceptualise DES (termed saturation). The end result of focus groups is a detailed description of how the symptomatic population conceptualise and understand DES (Gehlbach and Brinkworth, 2011). Participant responses are documented by taking written notes and / or audio recordings so all conversations can be replayed and transcribed verbatim. However, focus groups have some limitations; the quality of the discussion depends on the skill of the facilitator, some outspoken individuals may attempt to dominate the discussion, and conducting multiple focus groups results in large volumes of qualitative data which is very time-consuming for the researcher to analyse (Leung and Savithiri, 2009).

8.3.1 Methods

8.3.1.1 Participants

The study adhered to the tenets of the Declaration of Helsinki of 1975 and was approved by Aston University's Health and Life Sciences Research Ethics Committee (reference number HLS21160) and The University of Auckland's Health and Life Sciences Research Ethics Committee (reference number AH27539). Participants were recruited from both universities and the general public and were enrolled following explanation of the study and after providing written consent. Participants were eligible for inclusion in the study if they were aged 18 years or older and classified as experiencing DES, based on the Computer Vision Syndrome Questionnaire (CVS-Q) score of ≥ 6 at baseline (Seguí Mdel et al., 2015). Pregnant women, and any individuals with new or unstable general health conditions and / or medications and / or eye disease were excluded from the study. A total of 29 participants were recruited.

8.3.1.2 Examination protocol

The study was qualitative in nature. 4 focus group sessions were conducted online via Microsoft Teams. 2 facilitators (Aston University: Prof. James Wolffsohn and Danielle Beeson. The University of Auckland: Prof. James Wolffsohn and Prof. Jennifer Craig) were present during the focus group sessions. The Microsoft Teams call was automatically transcribed, the key points / themes were extracted within 1 month and the transcript was then deleted.

During the focus group discussion, the participants were encouraged to talk about DES in their own words. They were then shown a list of items which have been used in previous DES questionnaires (Table 8.1) and were subsequently asked the following questions.

Symptoms:
"We circulated a list of previously used questions to assess digital eye strain.

- *Were there any that you struggled to understand the meaning of or didn't have a suitable option to report?*
- *Were there any that you strongly agreed with or felt were not relevant to you?*
- *Were there any symptoms you get that are not on the list?*
- *Is this the best way to rate the impact that digital eye strain has on you, or might it be better to report after how long the symptom typically occurs or gets worse?"*

Impact and support:

- *"What impact does digital eye strain have on your life and how long do these impacts last after using a digital device?*
- *Have you found any strategies that help to reduce your digital eye strain*
- *Where do you look for support to relieve your digital eye strain?"*

Open discussion:
"Is there anything else you think we have missed from this discussion that could be important to digital eye strain assessment?"

8.3.2 Results

8.3.2.1 Symptoms

"Were there any (items) that you struggled to understand the meaning of or didn't have a suitable option to report?"

Some participants struggled to understand the meaning of 'foreign body sensation'. Once it was explained to them, they thought the phrase 'feels like there is something in my eye' is more relatable to the average layperson. Several participants said the item 'strange feeling around the eyes / pressure' was vague and would be unsure how to respond to it and there was also some confusion around 'irritation / burning / hurt / pain' so the term 'general ocular discomfort' was suggested instead.

"Were there any (items) that you strongly agreed with or felt were not relevant to you?"

All participants thought it was unnecessary to ask about blurred vision in so much detail. Instead, they agreed that blurred vision at near / intermediate tended to be experienced towards the end of a typical working day. Some participants said excessive blinking was not a symptom of DES, instead it was a mitigation technique employed after prolonged periods of viewing a screen and was therefore irrelevant. Participants agreed that neck and shoulder pain are commonly experienced after prolonged screen use and should be asked together as one item, but they felt items 30 to 37 were separate musculoskeletal issues caused by poor posture / sitting too long and they would not associate these items with DES.

"Were there any symptoms you get that are not on the list?"

No new symptoms were reported.

“Is this the best way to rate the impact that digital eye strain has on you, or might it be better to report after how long the symptom typically occurs or gets worse?”

When assessing the symptomology of DES, the participants agreed that a dichotomous ‘yes / no’ scale is too simplistic and should not be employed. Instead, they suggested some form of numerical grading scale to assess the severity of symptoms. The participants reported that they are unsure as to when they first experience certain symptoms so felt this was not so relevant to ask.

	Item	Aston University, Focus group 1 N = 5	Aston University, Focus group 2 N = 7	The University of Auckland, Focus group 1 N= 9	The University of Auckland, Focus group 2 N = 8
		Tick if experienced			
1	Blurred vision at near / difficulty focusing at near	✓		✓	✓
2	Blurred vision at intermediate	✓	✓	✓	✓
3	Blurred vision at distance				
4	Blurred vision / difficulties in seeing	✓		✓	✓
5	Difficulty in vision post-screen use / issues with colours		✓		
6	Sight worsening				
7	Difficulty in refocusing from one distance to another	✓	✓	✓	✓
8	Double vision		✓		✓
9	Crossing your eyes		✓		✓
10	Eye strain	✓	✓	✓	✓
11	Dry eyes	✓	✓	✓	✓
12	Irritated / burning / stinging eyes	✓	✓	✓	✓
13	Eye fatigue / tired eyes	✓	✓	✓	✓
14	Eyes hurt / eye pain	✓	✓	✓	✓
15	Photophobia	✓	✓	✓	✓

16	Headache	✓	✓	✓	✓
17	Strange feeling around the eyes / pressure		✓		
18	Numbness				
19	Dizziness				
20	Excessive blinking		✓		✓
21	Eyelid twitching		✓		
22	Heavy eyes / eyelids	✓	✓	✓	✓
23	Watery eyes / tearing		✓		✓
24	Eye redness	✓	✓	✓	✓
25	Itchy eyes	✓	✓	✓	✓
26	Foreign body sensation				✓
27	Coloured halos around objects				
28	Neck pain	✓	✓	✓	✓
29	Shoulder pain	✓	✓	✓	✓
30	Elbow/Forearm pain				
31	Hand/wrist pain				
32	Finger(s) pain				
33	Upper back pain				

34	Lower back pain		✓		
35	Thighs/knees pain				
36	Lower leg pain				
37	Ankle/foot pain		✓		
38	Insomnia			✓	✓
39	Depression			✓	
40	Pain, stiffness, numbness or tingling in the neck / shoulder / back				
41	Nausea / sickness				✓
42	Inability to hold objects well				
43	Difficulty to write using a pen				

Table 8.2. Table showing the responses of the focus group discussions to the different questionnaire items.

8.3.2.2 Impact and support

"What impact does digital eye strain have on your life and how long do these impacts last after using a digital device?"

A typical working day for the focus group participants involved using desktop computers / laptops and smartphones for up to 8 hours. Some participants reported that their DES symptoms stopped almost immediately after ceasing digital device use whereas others said some symptoms persisted well after their working day had ended. Subsequently, this impacted their 'downtime' so instead of watching TV programmes / films, some listen to podcasts or partake in other activities which avoid further digital device usage.

"Have you found any strategies that help to reduce your digital eye strain?"

Most participants reported taking a 10- to 15-minute break from digital devices during their lunchbreak. None of the participants followed the 20/20/20 rule stating it was not feasible due to their intense workloads; they only consider taking a break when they start to experience symptoms. Once symptoms start, they tend to use OTC artificial tears / eye sprays. Matching the screen brightness to the ambient room lighting and viewing a larger screen at a greater working distance helped reduce symptoms in some participants. Other participants said they have used blue light control screen filters in the past, but these did not seem to help. The participants agreed that their symptoms tend to be worse when working in an air-conditioned office as opposed to working from home. If symptoms persist in the evening after work, some participants used OTC artificial tears / sprays, and a heated eye mask.

"Where do you look for support to relieve your digital eye strain?"

Most participants sought advice from online resources or visiting an Optometrist.

"Is there anything else you think we have missed from this discussion that could be important to digital eye strain assessment?"

Some participants suggested that employers have a duty of care to raise awareness about DES and they should offer appropriate help, advice and support to their employees.

8.4 Unify the literature review and focus groups

Stage 3 involves merging the results of the literature review and focus groups. The final definition and list of indicators should be comprehensive, reflecting both the literature and the opinions of the focus group population (Gehlbach et al., 2010, Gehlbach and Brinkworth, 2011).

The literature review identified 16 different questionnaires which were used in various DES / CVS / VF studies. The most frequently asked items (featuring in ≥ 50 % of the identified questionnaires; see figure 8.2) are listed below.

- Blurred vision
- Dry eyes
- Irritated / burning / stinging eyes
- Eye redness
- Double vision
- Headache
- Eyes hurt / eye pain
- Eye strain
- Watery eyes / excessive tearing

The most frequently experienced items identified from the focus group discussions are listed below.

- Blurred vision at near / intermediate
- Difficulty in refocusing from one distance to another
- Eye strain
- Dry eyes
- Irritated / burning / stinging eyes
- Eye fatigue / tired eyes
- Eyes hurt / eye pain
- Photophobia
- Headache
- Heavy eyes / eyelids
- Eye redness
- Itchiness
- Neck and shoulder pain

Unifying the results, the list of items to be considered for the new DES questionnaire are.

- Blurred vision
- Blurred vision at near / intermediate
- Difficulty in refocusing from one distance to another
- Double vision
- Dry eyes
- Watery eyes / excessive tearing
- Eye redness
- Itchiness
- Irritated / burning / stinging eyes
- Eyes hurt / eye pain
- Eye fatigue / tired eyes
- Heavy eyes / eyelids
- Eye strain
- Headache
- Photophobia
- Neck and shoulder pain

8.5 Develop items

The aim of stage 4 is to develop items that represent DES in an ‘easy to understand’ language (Gehlbach and Brinkworth, 2011). Careful consideration needs to be given regarding item order (Şahin, 2021), item wording (Zeng et al., 2020), and whether open or closed-ended approaches are used or if ranking or rating tasks are utilised instead (Hyman and Sierra, 2016).

As DES has a multifactorial aetiology, it seemed appropriate to group the unified items into symptoms associated with uncorrected refractive errors and binocular vision anomalies, dry eye disease and musculoskeletal issues.

Uncorrected refractive errors and binocular vision anomalies

- Blurred vision
- Blurred vision at near / intermediate
- Difficulty in refocusing from one distance to another
- Eye fatigue / tired eyes
- Eye strain

- Double vision
- Headache

Dry eye disease

- Irritated / burning / stinging eyes
- Watery eyes / excessive tearing
- Itchiness
- Eye redness
- Eyes hurt / eye pain
- Photophobia
- Dry eyes
- Heavy eyes / eyelids

Musculoskeletal issues

- Neck and shoulder pain

The focus group participants and literature review identified neck and shoulder pain as the most significant musculoskeletal issue associated with DES (Falkenberg et al., 2020, Das et al., 2022, Kaur et al., 2022, Moore et al., 2024), leading to the exclusion of other musculoskeletal options.

The increase in DES seems to be proportional to the increase in daily hours of digital device use (Wolffsohn et al., 2023). Although the amount of time spent on digital devices appears to be critical for the development of DES symptoms, the CVS-Q does not ask about daily screen time, nor does it specifically ask about the number of days a week the symptoms are experienced. The focus group participants reported a preference for a numerical grading scale to assess the severity of symptoms. Though no scale is suitable for all patients, a 0-10 scale for the clinical assessment of pain intensity in adult patients is favoured within medicine (Dalton and McNaull, 1998). The validated 11-point box scale, also known as the Numeric Pain Rating Scale (NPRS), utilises this and categorises the severity of pain into ‘no pain = 0, mild pain = 1-3, moderate pain = 4-6, and severe pain = 7-10’ (Jensen et al., 1989).

Taking the above points into consideration, a 20-item, first draft questionnaire was designed (Figure 8.4). It asks about daily screen time, the frequency of symptoms (occurring within a week) and the intensity of symptoms using an adapted version of the NPRS.

	In a typical day, how many hours do you spend using digital devices? *(The following devices are considered to be digital devices; desktop computers, laptops, tablet computers, smartphones, smart watches, TV, games consoles, VR headsets and e-readers)*											
	Never	< 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours	6 to 8 hours	8 to10 hours	>10 hours				
	When using digital devices, how often do you experience the symptom in a typical week?								**How intense is the symptom?** *(On a scale of 0-10, none = 0, mild intensity = 1-3, moderate intensity = 4-6, and severe intensity = 7-10)*			
Symptom	Never	Some days	Most days	Every day					None	Mild	Moderate	Severe
Blurred vision												
Blurred vision at near												

Blurred vision at intermediate												
Difficulty in refocusing from one distance to another												
Eye fatigue												
Tired eyes												
Eye strain												
Double vision												
Headache												
Irritated eyes												
Burning eyes												

Stinging eyes												
Watery eyes												
Itchy eyes												
Eye redness												
Eye pain												
Photophobia												
Dry eyes												
Heavy eyes / eyelids												
Neck and shoulder pain												

Figure 8.4. The first draft version of the new digital eye strain questionnaire.

	In a typical day, how many hours do you spend using digital devices? *(The following devices are considered to be digital devices; desktop computers, laptops, tablet computers, smartphones, smart watches, TV, games consoles, VR headsets and e-readers)*											
	Never	< 1 hour	1 to 2 hours	2 to 4 hours	4 to 6 hours	6 to 8 hours	8 to10 hours	>10 hours				
						X						
	When using digital devices, how often do you experience the symptom in a typical week?								**How intense is the symptom?** *(On a scale of 0-10, none = 0, mild intensity = 1-3, moderate intensity = 4-6, and severe intensity = 7-10)*			
Symptom	Never	Some days	Most days	Every day					None	Mild	Moderate	Severe
Blurred vision	**X**											
Blurred vision at near	**X**											

Blurred vision at intermediate	**X**											
Difficulty in refocusing from one distance to another		**X**								**X**		
Eye fatigue		**X**								**X**		
Tired eyes			**X**								**X**	
Eye strain			**X**								**X**	
Double vision	**X**											
Headache		**X**									**X**	
Irritated eyes		**X**								**X**		
Burning eyes		**X**								**X**		

Stinging eyes		X								X		
Watery eyes	X											
Itchy eyes	X											
Eye redness		X								X		
Eye pain		X								X		
Photophobia	X											
Dry eyes			X							X		
Heavy eyes / eyelids		X									X	
Neck and shoulder pain			X								X	

Figure 8.5. An example of how to complete the new DES questionnaire.

8.6 Conduct validation

Once the construct has been defined and draft items have been written, an important step in the development of a new questionnaire is to begin collecting validity evidence based on the questionnaire's content. Using experts (authors from the reference list of the literature review or researchers actively involved in the research of DES) to systematically review the questionnaire's content can substantially improve the overall quality and representativeness of the questionnaire's items. A minimum of 6 experts is usually recommended (Rubio et al., 2003).

8.7 Conduct cognitive interviews

Cognitive interviewing is a technique that is used to improve and refine questionnaire items. The two major techniques for conducting cognitive interviews are the 'think-aloud' technique where respondents verbalise every thought they have while answering each item (Willis and Artino, 2013) and 'verbal probing' where the interviewer administers a series of questions designed to elicit specific information (Willis and Artino, 2013). The data is then analysed and any revisions to the questionnaire are made.

8.8 Conduct pilot testing

The final step in developing a new questionnaire is to conduct pilot testing; the data can then be analysed to assess the distribution of item responses and the internal consistency reliability (Cronbach α coefficient) of the grading scales (Jenn, 2006, Rickards et al., 2012). The final questionnaire design is usually comprehensively informed by any useful insight gathered from the pilot study.

Chapter 9. Conclusions and plans for future work

9.1 General conclusions

DES encompasses a variety of visual and ocular symptoms that arise due to the prolonged use of digital devices. DES is a multifactorial condition and affected individuals require a detailed eye examination to establish the likely cause of their symptoms followed by the most appropriate management plan. The principal themes of the thesis was to determine the repeatability and reproducibility of the Bernell pocket CFF tester (Chapter 3), to determine if CFF can be used as an objective measure of DES (Chapters 4 & 5), to investigate the effect of commercially available privacy screen filters on DES symptoms (Chapters 4 & 5), to track visuo-ocular symptoms during prolonged (1-hour) digital tasks and assess how higher and lower cognitive load levels influence DES symptoms, productivity, and task accuracy (Chapter 6), to investigate the association between the symptoms and signs of DES, dry eye disease and convergence insufficiency (Chapter 7) and to commence the development of a novel DES questionnaire (Chapter 8).

9.1.1 Repeatability and reproducibility of the Bernell pocket critical flicker-fusion frequency tester

A clinical evaluation of the Bernell pocket CFF tester was undertaken to assess its value in the field of CFF and DES research. The small, handheld device uses white-black flicker and measures CFF thresholds between 35 Hz and 60 Hz, with a step size of 1 Hz. Despite being used in previously published studies (Tannen et al., 2015, Benassi et al., 2021), the work undertaken in Chapter 3 appears to be the first to have investigated the device's intraexaminer repeatability and reproducibility. The results showed that the Bernell pocket CFF tester has good intraexaminer repeatability and reproducibility (α = 0.97, ICC = 0.97, CR = 1.55 and CV = 4%) so practitioners can confidently use it to measure CFF thresholds within clinical practice and future research studies.

Currently there are no widely accepted objective measures of DES. As CFF is a recognised measure of fatigue and mental workload (Thackray, 1985, Luczak and Sobolewski, 2005), it would not be unreasonable to suggest that changes in flicker-fusion values could be used as an objective measure of DES. Utilising the validated Bernell pocket CFF tester (Chapter 3), CFF measures were taken before and after a continuous, intensive visual search laptop task. Despite DES symptoms worsening after 60-minutes (F = 5.580, p = 0.008), CFF values did not change (F = 0.289, p = 0.751). Although CFF has been used as a measure of visual fatigue in previous studies (Maeda et al., 2011, Benedetto et al., 2013, Gautam, 2020), the

findings supported two recent studies which concluded that CFF measures cannot be used as an objective measure of DES (Yan and Rosenfield, 2022, Singh et al., 2023).

9.1.2 Privacy screen filters do not provide any benefit to digital eye strain sufferers after an intensive 30- and 60-minute laptop task

At present there is no evidence to support the use of blue-blocking filters as a clinical treatment for DES (Rosenfield et al., 2020, The College of Optometrists., 2022). Similarly, studies investigating the efficacy of anti-reflection screens and / or filters in reducing visual fatigue symptoms have produced conflicting results (Scullica et al., 1995, Hladký and Procházka, 1998, Sheedy et al., 2003, Reddy et al., 2013, Shantakumari et al., 2014, Ranasinghe et al., 2016a). The purpose of Chapters 4 and 5 was to determine if a novel, commercially available privacy screen filter reduces DES symptoms when using a laptop compared to an earlier generation privacy screen filter and a clear placebo filter. In Chapter 4, participants completed an intensive 30-minute visual search task. After the task, no improvement in symptom severity was observed, leading to the implementation of a longer, 60-minute task. Chapter 5 demonstrated that 60-minutes of continuous digital device made DES symptoms worse ($F = 5.580$, $p = 0.008$). The findings were unable to provide evidence to support the use of privacy screen filters as a clinical treatment for DES.

9.1.3 Digital eye strain symptoms worsen during prolonged digital tasks, associated with a reduction in productivity

The relationship between visuo-ocular symptoms, productivity, and work accuracy has previously been unclear. Chapter 5 demonstrated that the severity of DES symptoms increases with the prolonged use of digital devices, particularly after 60-minutes of continuous task engagement. The results aligned with Chapter 6's findings that visuo-ocular symptoms worsen after 1-hour of continuous digital device usage in individuals with DES, with a faster rate for more demanding tasks. Interestingly, despite an increase in symptoms, work accuracy did not seem to be significantly impacted. Chapter 6 also revealed that participants were able to complete nearly twice as many tasks in the lower cognitive load condition compared to the higher cognitive load condition. This suggests that with lower cognitive demands, participants required less mental effort to process information, resulting in greater task efficiency. Interestingly, both conditions experienced a similar decline in task completion over time (a reduction in productivity), indicating that time-related fatigue or

reduced attention may affect performance in both conditions in a similar way, regardless of cognitive load.

Although the 60-minute task was significantly longer than those in previous studies (Collier and Rosenfield, 2011, Palavets and Rosenfield, 2019, Gautam, 2020, Redondo et al., 2020, Rosenfield et al., 2020, Padavettan et al., 2021, Lin et al., 2022, Talens-Estarelles et al., 2022b, Yan and Rosenfield, 2022), visuo-ocular symptoms had not yet plateaued by the end of the task. Given that many individuals spend considerably more time in front of screens, the 60-minute task may not fully capture the severity of symptoms in real-life settings. Nonetheless, the study provided valuable insight into the progression of symptoms and their impact on productivity and provided meaningful results for the purpose of the thesis.

9.1.4 Association between symptoms and signs of digital eye strain, dry eye disease and convergence insufficiency

It was demonstrated in Chapter 7 that individuals with DES are also likely to be symptomatic of dry eye disease and / or convergence insufficiency. Therefore, it is advisable for primary care Optometrists to conduct thorough dry eye and binocular vision assessments when examining patients with DES. Individuals with higher CVS-Q scores (11.7 ± 3.8) tended to exhibit signs of mild MGD and moderate LWE, which are indicative of evaporative dry eye disease. In such cases, appropriate treatments, such as artificial tears containing liposomes, lid hygiene, and lid warming combined with moderate to firm massage, should be implemented to alleviate symptoms (Nichols et al., 2011, TFOS, 2017, Semp et al., 2023). If binocular vision anomalies are detected, it is recommended to consider appropriate binocular vision therapy or, if necessary, referral to an Orthoptist for further management.

Symptoms of mental fatigue, including attention difficulties, anxiety, blurred vision, ocular pain, and dryness (Stack et al., 2017), often overlap with those of DES, dry eye disease and convergence insufficiency. Therefore, if primary care Optometrists are unable to identify signs of dry eye disease or binocular vision issues in symptomatic patients, they may consider a holistic approach. This could involve recommending lifestyle changes such as improving sleep quality, maintaining a regular exercise routine, ensuring balanced nutrition, and taking frequent breaks from digital devices (Health and Safety Executive, 2021b).

9.1.5 Developing a new digital eye strain questionnaire

When assessing DES symptomology, it is important to identify whether symptoms are specific to digital device usage, ocular surface disease, performing a sustained near-vision task, or a combination of some or all these variables. Throughout the thesis, the most commonly used DES questionnaire, the CVS-Q, was used to identify individuals with DES (Chapters 4, 5, 6, 7 & 8) and to track their symptoms (Chapters 4, 5 & 7). However, it became apparent that the CVS-Q fails to differentiate symptoms specific to when individuals are performing a digital task. Hence the author of the thesis aimed to address this limitation in Chapter 8 by commencing the development of a new DES questionnaire. A systematic review of existing literature was undertaken, identifying 45 items from 18 different questionnaires. Multiple focus groups were conducted in both the UK and New Zealand (N = 29) to gather insights into how the symptomatic population conceptualises and understands DES. The results of the literature review and focus group discussions were then unified resulting in a 20-item, first draft questionnaire that asks about daily screen time and the frequency and intensity of symptoms, offering a more tailored approach to assessing digital device-related symptoms.

9.2 Plans for future research

9.2.1 Completing the development of a new digital eye strain questionnaire

As discussed in section 9.1.5, the author of the thesis commenced the development of a new DES questionnaire. For the thesis, the first 4 stages were completed; a systematic review of the literature, conducting multiple focus groups, unifying the literature review and focus group discussions and developing questionnaire items and response scales. Since this questionnaire is intended for global use, additional focus groups representing a wide range of demographics (students, older adults, and a variety of working professionals) will be conducted, with plans already in place for sessions in the USA, Europe, South America, and Asia. After these are completed, the process of integrating the literature review with the focus group discussions, as well as refining the questionnaire items and response scales, will be repeated. Symptom severity will be determined by combining the responses to the items in the two rating scales by multiplying their respective scores (frequency x intensity) and further refinement to the weighting scheme will occur through Rasch analysis.

The next stage involves validating the content of the questionnaire by convening a group of at least six experts (Rubio et al., 2003). These experts, either face-to-face or virtually, will

review the questionnaire's content and its presentation. Their feedback will help refine the questionnaire and provide recommendations for improvements. Before pilot testing the questionnaire, cognitive interviewing will be undertaken; this involves testing the questionnaire on a small sample of respondents and asking them to verbalise their thought process while answering each item. The goal is to understand how the respondents interpret the items and to identify any issues with clarity, comprehension, or relevance. Follow-up questions will also be asked to gather specific information on how the items are understood (Willis and Artino, 2013). Based on this feedback, revisions to the questionnaire will be made.

The next step is to conduct pilot testing on a larger sample. The data collected will be analysed to assess the distribution of item responses, the internal consistency of the questionnaire and the test-retest reliability (Jenn, 2006, Rickards et al., 2012). The pilot test provides insight into whether the items are measuring the intended construct consistently and whether any further revisions are needed.

Since the new questionnaire is intended to be used globally, linguistic validation is also required. This process involves using bilingual translators, who are native speakers, to translate the questionnaire into their mother tongue ensuring that it maintains its intended meaning across different cultures and languages. The translations are then reviewed by an expert committee to ensure that the translated versions are equivalent to the original (Tsang et al., 2017). After the translations are finalised, cognitive interviewing is repeated with the translated versions, followed by additional pilot testing to ensure that the translations work effectively in practice.

By carefully validating the content, refining items through cognitive interviewing, and testing the reliability amongst large samples, the resulting questionnaire will be better equipped to assess DES symptoms across different populations and languages. The new DES questionnaire can be incorporated into the history and symptoms section of a consultation, allowing practitioners to quickly identify symptomatic patients. This will enable practitioners to offer recommendations, such as lifestyle modifications, ergonomic adjustments, treatment for underlying eye conditions, and prescribing glasses if needed, all aimed at improving the patient's quality of life when using digital devices.

9.2.2 Can contrast sensitivity be used as an objective measure of digital eye strain?

At the time of writing, there appears to be a lack of published research investigating the effect of modern-day digital devices and their usage patterns on contrast sensitivity. As contrast sensitivity can reflect cognitive function (Ridder et al., 2017), digital device usage may lead to a temporary decrease in contrast sensitivity, indicating mental fatigue, which was illustrated in Chapter 6 as a reduction in task productivity.

To test whether contrast sensitivity can be used as an objective measure of DES, individuals with DES (CVS-Q score $\geq$ 6) will be recruited. Baseline symptomology and contrast sensitivity measures (utilising the gold standard Pelli-Robson contrast sensitivity chart (Donahue et al., 2022)) will be taken before the digital task. As shown in Chapters 5 and 6, symptoms worsened over a 1-hour period therefore participants will undertake the same intensive laptop task (as used in Chapters 4, 5 & 6) continuously for 1-hour. Post-task symptomology and contrast sensitivity measurements will be taken immediately after the task. The data will then be analysed to determine if there is a significant change in contrast sensitivity pre- and post-task. If no change is found, it could suggest that modern digital devices have minimal or no effect on contrast sensitivity. If contrast sensitivity decreases after the task, contrast sensitivity could potentially be used as an objective measure of DES.

9.2.3 Investigating visuo-ocular symptoms, productivity and work accuracy when using a colour e-ink display

As discussed in section 1.2.7, electronic paper, also known as e-ink, is a type of reflective display technology that mimics the appearance of ordinary ink on paper. E-ink displays produce very little glare (Wolffsohn et al., 2023) and previous studies have shown that DES is less apparent when using an e-reader (monochrome e-ink display) (Siegenthaler et al., 2012a, Benedetto et al., 2013, Talens-Estarelles et al., 2020). DASUNG, a Chinese High-Tech enterprise recently launched the world's first ultra-fast colour e-ink computer monitor (25.3-inch) retailing at $1,749.00 USD (DASUNG, 2024). Although currently only compatible with Windows operating system, customer reviews highlight the monitor's ability to reduce eye strain and promote visual comfort. However, at the time of writing, there appears to be a lack of published research exploring the impact of colour e-ink displays on DES symptoms, work productivity, and accuracy - areas already explored within the thesis with LED-LCD displays (Chapter 6). Therefore, it would be of great interest to repeat Chapter 6's investigation to determine if there are any notable differences in symptoms, productivity and work accuracy when using a colour e-ink display as opposed to LED-LCD displays. By doing

so, the research study would be able to provide comprehensive data on the differences between these two types of displays (LED-LCD and colour e-ink) in terms of user experience and performance metrics.

9.3 Concluding statement

The thesis has provided a comprehensive evaluation of DES. Chapter 1 explored the history, ownership and usage trends of digital devices, examined the ocular and non-ocular risk factors for DES and discussed other health risks associated with digital device usage. The experimental investigations validated the Bernell pocket CFF tester (Chapter 3) and showed that CFF measures cannot be used as an objective measure of DES (Chapter 5), demonstrated that commercially available privacy screen filters cannot be marketed as a clinical treatment for DES (Chapters 4 & 5), prolonged (1-hour) digital tasks lead to worsening visuo-ocular symptoms and decreased productivity (Chapter 6), and individuals with DES are often also symptomatic of dry eye disease and / or convergence insufficiency (Chapter 7). The work undertaken within the thesis highlighted the need for a new, validated questionnaire to better assess and diagnose DES so the author of the thesis began the process of developing a new questionnaire (Chapter 8) to facilitate future refinement in different languages and cultures.

Appendices

Appendix 1: Computer Vision Syndrome Questionnaire (CVS-Q)

To be completed by the participant:

Indicate whether you experience any of the following symptoms during the time you use the computer at work. For each symptom, mark with an **X**:

a. First, the frequency, that is, how often the symptom occurs, considering that:

NEVER = the symptom does not occur at all

OCCASIONALLY = sporadic episodes or once a week

OFTEN OR ALWAYS = 2 or 3 times a week or almost every day

b. Second, the intensity of the symptom:

Remember: if you indicated NEVER for frequency, you should not mark anything for intensity.

	a. Frequency			**b.** Intensity	
	NEVER	OCCASIONALLY	OFTEN OR ALWAYS	MODERATE	INTENSE
1 Burning					
2 Itching					
3 Feeling of a foreign body					
4 Tearing					
5 Excessive blinking					
6 Eye redness					
7 Eye pain					

8 Heavy eyelids					
9 Dryness					
10 Blurred vision					
11 Double vision					
12 Difficulty focusing for near vision					
13 Increased sensitivity to light					
14 Coloured halos around objects					
15 Feeling that sight is worsening					
16 Headache					

Courtesy of (Seguí Mdel et al., 2015).

Appendix 2: Ocular Surface Disease Index questionnaire (OSDI)

Circle the number in the box that best represents each answer.

Have you experienced any of the following *during the last week*:

	All of the time	Most of the time	Half of the time	Some of the time	None of the time	
1. Eyes that are sensitive to light?	4	3	2	1	0	
2. Eye that feel gritty?	4	3	2	1	0	
3. Painful or sore eyes?	4	3	2	1	0	
4. Blurred vision?	4	3	2	1	0	
5. Poor vision?	4	3	2	1	0	

Have problems with your eyes limited you in performing any of the following *during the last week*:

6. Reading?	4	3	2	1	0	**N/A**
7. Driving at night?	4	3	2	1	0	**N/A**
8. Working with a computer or a bank machine (ATM)	4	3	2	1	0	**N/A**
9. Watching TV?	4	3	2	1	0	**N/A**

Have your eyes felt uncomfortable in any of the following situations *during the last week*:

10. Windy conditions?	4	3	2	1	0	**N/A**
11. Places or areas with low humidity (very dry)?	4	3	2	1	0	**N/A**
12. Areas that are air conditioned?	4	3	2	1	0	**N/A**

Courtesy of (Walt et al., 1997, Schiffman et al., 2000).

Appendix 3: The revised Convergence Insufficiency Symptom Survey questionnaire (CISS)

Clinician instructions: Read the following subject instructions and then each item exactly as written. If subject responds with “yes” - please qualify with frequency choices. Do not give examples.

Subject instructions: Please answer the following questions about how your eyes feel when reading or doing close work.

		Never (not very often)	Infrequently	Sometimes	Fairly often	Always
1.	Do your eyes feel tired when reading or doing close work?					
2.	Do your eyes feel uncomfortable when reading or doing close work?					
3.	Do you have headaches when reading or doing close work?					
4.	Do you feel sleepy when reading or doing close work?					
5.	Do you lose concentration when reading or doing close work?					

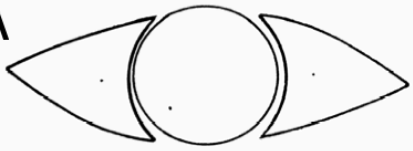
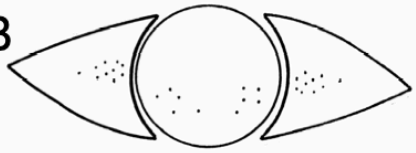
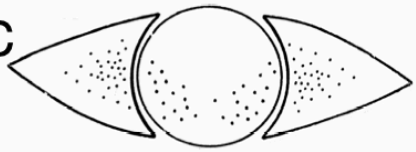
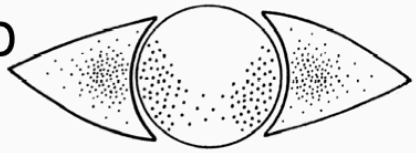
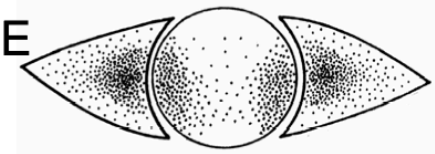
6.	Do you have trouble rememberin g what you have read?					
7.	Do you have double vision when reading or doing close work?					
8.	Do you see the words move, jump, swim or appear to float on the page when reading or doing close work?					
9.	Do you feel like you read slowly?					
10.	Do your eyes ever hurt when reading or doing close work?					
11.	Do your eyes ever feel sore when reading or doing close work?					
12.	Do you feel a "pulling" feeling around your eyes when reading or doing close work?					

13.	Do you notice the words blurring or coming in and out of focus when reading or doing close work?					
14.	Do you lose your place while reading or doing close work?					
15.	Do you have to re-read the same line of words when reading?					
		__x0	**__x1**	**__x2**	**__x3**	**__x4**

TOTAL SCORE _____

Courtesy of (Borsting et al., 2003).

Appendix 4: Oxford grading scale

PANEL	GRADE	CRITERIA
A 	0	Equal to or less than panel A
B 	I	Equal to or less than panel B, greater than A
C 	II	Equal to or less than panel C, greater than B
D 	III	Equal to or less than panel D, greater than C
E 	IV	Equal to or less than panel E, greater than D
>E	V	Greater than panel E

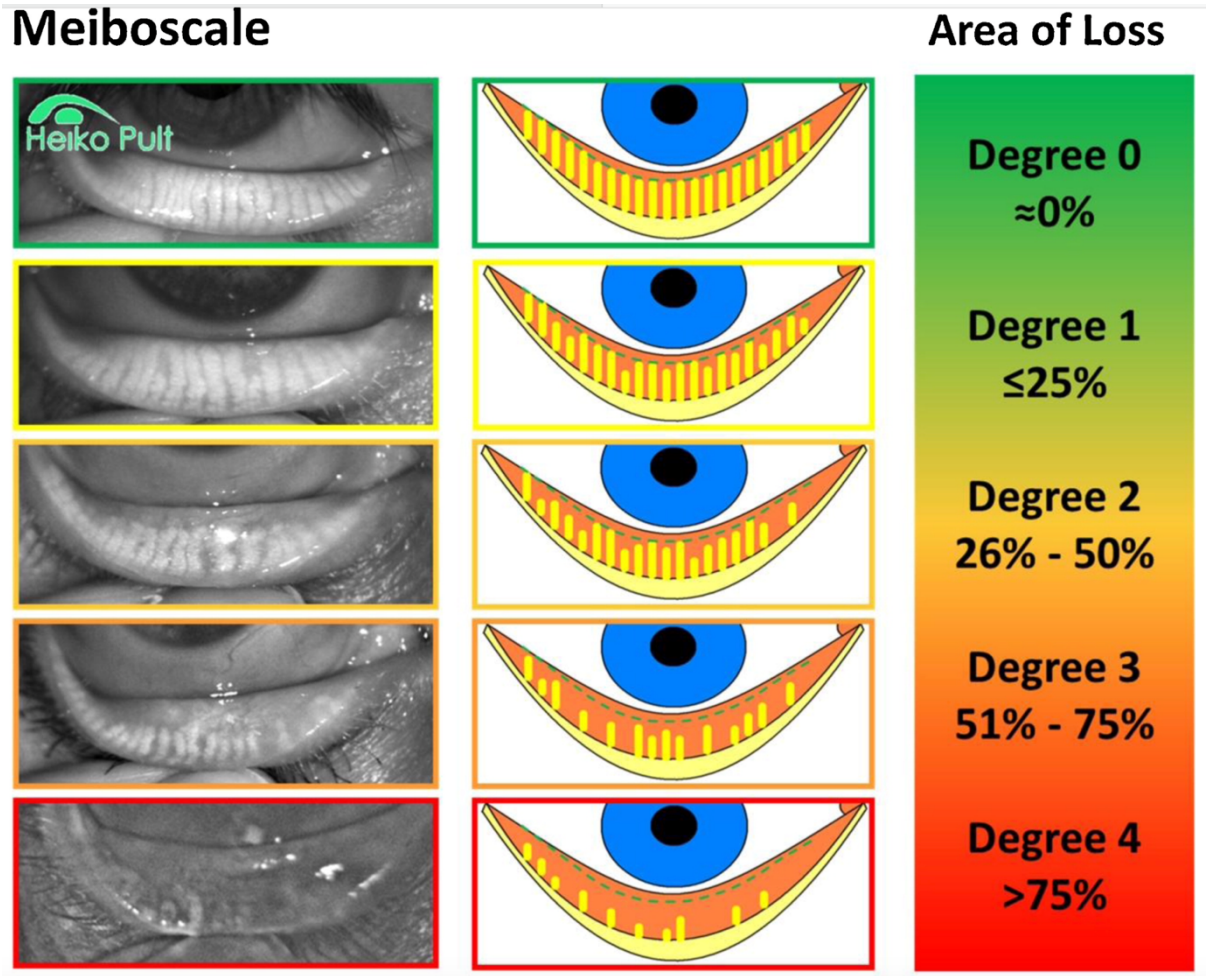
Courtesy of (Bron et al., 2003).

Appendix 5: Korb lid wiper epitheliopathy grading scale

Horizontal length of staining	Grade	Sagittal width of staining	Grade
<2 mm	0	<25% of the lid wiper	0
2-4 mm	1	25% - <50% of the lid wiper	1
5-9 mm	2	50% - <75% of the lid wiper	2
>10 mm	3	≥75% of the lid wiper	3

Courtesy of (Korb et al., 2005, TFOS, 2017).

Appendix 6: Pult 5-grade meiboscale



Courtesy of (Pult and Riede-Pult, 2013).

Appendix 7: High and low load task construction

An example of a high load task - participants were instructed to highlight the letter ‘N’. If they could not see it, they were instructed to highlight ‘N is missing’ and move onto the next task. 3 grids were presented on each page.

K	H	Z	W	M	
M	V	H	M	W	
Z	M	W	K	H	N is missing
W	K	N	V	Z	
H	Z	V	W	K	

H	V	Z	K	W	
K	M	W	H	Z	
W	H	M	V	W	N is missing
M	Z	V	K	N	
K	W	H	V	Z	

W	H	Z	K	V	
K	V	W	H	Z	
V	H	K	Z	H	N is missing
M	N	V	W	K	
Z	W	K	M	V	

An example of a low load task – participants were instructed to highlight the letter ‘N’. If they could not see it, they were instructed to highlight ‘N is missing’ and move onto the next task. 6 grids were presented on each page.

O	K	O	O	O
O	O	V	O	M
O	O	O	O	O
O	O	N	O	O
O	O	V	O	O

N is missing

H	H	O	O	O
O	M	O	O	O
O	K	O	O	O
O	O	O	O	N
O	O	O	O	O

N is missing

O	O	O	O	Z
O	O	O	O	O
O	O	O	O	O
O	N	O	O	O
Z	O	H	Z	O

N is missing

O	O	O	M	O
O	O	O	Z	O
O	H	O	O	O
O	O	Z	K	O
O	O	O	O	O

N is missing

O	N	H	O	O
O	O	O	O	W
O	O	O	O	O
O	O	O	O	O
H	O	O	Z	O

N is missing

O	O	W	O	O
O	O	O	O	N
O	O	O	O	W
O	O	M	O	H
O	O	O	O	O

N is missing

Appendix 8: Publications

Peer-reviewed journal publications

Danielle Beeson, James S. Wolffsohn, Thameena Baigum, Talaal Qureshi, Serena Gohil, Rozia Wahid, Amy L. Sheppard (2024). Digital eye strain symptoms worsen during prolonged digital tasks, associated with a reduction in productivity, Computers in Human Behavior Reports, Volume 16, December 2024, 100489. https://doi.org/10.1016/j.chbr.2024.100489

David A Semp, **Danielle Beeson**, Amy L Sheppard, Debarun Dutta, James S Wolffsohn (2023). Artificial Tears: A Systematic Review, Clinical Optometry, 15: 9-27. https://doi.org/10.2147/OPTO.S350185

Optometry Today publication

Danielle Beeson, James S. Wolffsohn, Amy L. Sheppard (2024). Assessing and managing digital eye strain in clinical practice, Optometry Today, February / March 2024, Volume 64:01, 66-69. https://www.aop.org.uk/ot/cpd/2024/01/22/assessing-and-managing-digital-eye-strain-in-clinical-practice/article

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