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TFOS Lifestyle: Impact of the digital environment on the ocular surface

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ABSTRACT

Eye strain when performing tasks reliant on a digital environment can cause discomfort, affecting productivity and quality of life. Digital eye strain (the preferred terminology) was defined as "the development or exacerbation of recurrent ocular symptoms and/or signs related specifically to digital device screen viewing". Digital eye strain prevalence of up to 97% has been reported, due to no previously agreed definition/diagnostic criteria and limitations of current questionnaires which fail to differentiate such symptoms from those arising from non-digital tasks. Objective signs such as blink rate or critical flicker frequency changes are not 'diagnostic' of digital eye strain nor validated as sensitive. The mechanisms attributed to ocular surface disease exacerbation are mainly reduced blink rate and completeness, partial/uncorrected refractive error and/or underlying binocular vision anomalies, together with the cognitive demand of the task and differences in position, size, brightness and glare compared to an equivalent non-digital task. In general, interventions are not well established; patients experiencing digital eye strain should be provided with a full refractive correction for the appropriate working distances. Improving blinking, optimizing the work environment and encouraging regular breaks may help. Based on current, best evidence, blue-light blocking interventions do not appear to be an effective management strategy. More and larger clinical trials are needed to assess artificial tear effectiveness for relieving digital eye strain, particularly comparing different constituents; a systematic review within the report identified use of secretagogues and warm compress/humidity goggles/ambient humidifiers as promising strategies, along with nutritional supplementation (such as omega-3 fatty acid supplementation and berry extracts).

1. Introduction and terminology

The digital environment is now ubiquitous in our daily lives. The report is part of the Tear Film & Ocular Surface Society (TFOS) Workshop (www.tearfilm.org), entitled 'A Lifestyle Epidemic: Ocular Surface Disease,' which was undertaken to establish the direct and indirect impacts that everyday lifestyle choices and challenges have on ocular surface health. The goals of this report were: to clarify the terminology relating to the ocular effects of the digital environment (defined as any technology requiring viewing of a digital display for a cognitive task)

Abbreviations: CI, Confidence Interval; CSV-Q, Computer Vision Syndrome Questionnaire; CVS-F3, Computer Vision Syndrome: Form 3; CVSS17, Computer-Vision Symptom Scale; E-paper, Electronic paper; GRADE, Grading of Recommendations, Assessment, Development and Evaluations; USB, Universal Serial Bus.

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and the associated diagnostic criteria; to characterize the differences between digital screen and real-world viewing and the impact this has on the tear film, ocular surface and visual system; to assess the prevalence of digital environment-related effects on the eyes (particularly on the ocular surface), and the impact on productivity as well as quality of life implications; and to explore the mechanism of action driving the effects of the digital environment on the eyes (particularly the ocular surface). This information was summarised in a narrative style review that, wherever possible, refers to outcomes from high-quality systematic review (Level I) evidence. In alignment with the other TFOS Lifestyle Workshop reports, the Evidence Quality Subcommittee provided a comprehensive database of appraised Level 1 evidence judged to be of potential relevance, which was factored into the writing of the report [1]. In addition, the report includes a systematic review and meta-analysis that evaluates the evidence-base for proposed treatments/management strategies for reducing symptoms associated with digital device use.

While the term 'digital' is commonly used in the context of computers in contemporary society, its definition and contextual use has evolved over time. The word 'digital' derives from the Latin term *digitalis*, from *digitus* (meaning 'finger' or 'toe'). Its original meaning was "pertaining to numbers below ten" (mid-15th Century), to reflect finger counting. As described in the Online Etymology Dictionary [2,3], in the late 1930s, the definition of 'digital' expanded to the 'use of numerical digits' in recognition of early computer technologies that used data rather than analogue computation. By the 1940s, the term digital was frequently associated with recording and broadcasting methods, gradually evolving to its current embodiment describing electronic or computerized technologies more broadly [4].

The term 'digital device(s)' described electronic equipment that use (s) discrete, numerable data; this might be through receiving, storing, processing or sending digital information [5], typically via a computer. Common examples of digital devices include personal computers, televisions and mobile phones, but can also involve navigation systems, digital cameras and augmented reality systems. Of note, not all of them have screens, such as home controls/sensors. The term 'screen time' describes the period of time spent viewing or using digital devices with a display screen [6]. In practical terms, a 'digital environment' is generally considered a context or place that is enabled by technology and digital devices.

Digital environments are pervasive in modern life [7], and often involve extended periods of screen viewing time. Based on online survey data from early 2020, it was estimated that the average adult residing in the United States had access to at least 10 digital devices in their household [8], and would spend almost 8 h per day interacting with digital media [9]. Prevalent use of digital technologies is also evident amongst children and adolescents. For example, in a 2016 multi-national European study, two-thirds of three-year old children were reported to regularly interact with a digital device [10] and it is likely this has increased since this time. When viewing demands exceed the user's capability to view the task comfortably, visual symptoms can arise [11]. Changes to working environments due to the COVID-19 pandemic have led to even greater digital device use and a high prevalence of related symptoms [12]. In a cross-sectional study of >3000 US adults, self-reported screen time use was described to have increased by 20–30% during the pandemic [13].

The potential effect(s) of digital device use on eye health and vision have been of scientific and clinical interest for over 20 years [14]. It remains a prominent and increasingly relevant topic, as highlighted by several recent literature reviews [15–19]. The most commonly quoted definition is from the American Optometric Association that states "Computer vision syndrome, also referred to as digital eye strain, describes a group of eye- and vision-related problems that result from prolonged computer, tablet, e-reader and cell phone use." [20] However, this definition does not exclude those who experience these 'problems' when conducting similar non-digital tasks and key terms such as "prolonged" are not defined.

To clearly define the scope of the ocular associations for the *TFOS Lifestyle: Impact of the digital environment on the ocular surface* report, the term **'digital eye strain'** is defined as **"the development or exacerbation of recurrent ocular symptoms and/or signs related specifically to digital device screen viewing"**. Using this definition, digital eye strain can be considered a potential eventuality in a clinically healthy individual that occurs when using a digital device, or as a worsening of pre-existing ocular symptoms and/or signs due to digital device use. The term 'digital eye strain' has been used in preference to 'computer vision syndrome', which is also commonly used in the literature [21]; the latter was considered to have an implied specificity to computers rather than digital devices more generally. 'Syndrome' is fairly nebulously defined as "a number of symptoms occurring together" [2] and 'vision' the "sense of sight" [2], which is less appropriate terminology than 'strain' meaning to "over-exert" [2] relating to the 'eye'. Other past terminology includes: 'repetitive strain disorder' [22], but this implies it is repeated exposure that creates the problems, as does eye fatigue [23], for which there is no scientific backing; 'eye related pain' [24], but most individuals would not use this extreme terminology to describe their symptoms; 'asthenopia' [23,25], which is a weakness, or fatigue, of the eyes or vision - it has therefore been proposed that the term may be best confined to describing symptoms arising from a visual or ocular anomaly, rather than from purely extrinsic (e.g., environmental) factors [26]; even 'video game vision' has been proposed [27], but this would be a subset of digital eye strain.

Symptoms of digital eye strain are non-specific and heterogeneous, and include ocular tiredness, blur, ocular soreness, eye strain, ocular pain, burning, ocular dryness and light sensitivity [28,29]. Some definitions also include headache and neck/shoulder pain [30], however, these non-ocular symptoms were considered beyond the eye-specific definition relevant to this report. It has been proposed that eye strain symptoms may derive from two distinct mechanisms [31]: 'external' symptoms (such as dryness, tearing, irritation and burning) that have been linked to the ocular surface including dry eye disease [32] and contact lens induced dry eye [33], and 'internal' symptoms (such as blur, tiredness and ache) that have been associated with accommodation and/or binocular vision dysfunction [31]. There remains some ambiguity regarding the characteristic clinical sign(s) of digital eye strain, at least in part because its physiological basis is uncertain. As discussed in further detail in Section 6, it has been suggested that potential clinical indicators of digital eye strain may include measures of visual function (such as accommodation and convergence function, critical flicker fusion frequency and pupil responses) and ocular surface health (such as tear osmolarity, tear meniscus parameters, tear evaporation rate, tear breakup time, blinking characteristics and meibomian gland parameters) [34]. The present report focuses primarily on the effect(s) of human interaction with the digital environment on the ocular surface, acknowledging that it may be challenging to determine the source of non-specific symptoms (such as the blurred vision that may be due to either an ocular surface anomaly, an alteration within the binocular vision system, uncorrected refractive error or a change in refractive status).

2. Display technologies

2.1. Display type

2.1.1. Cathode ray tube (CRT) display

One of the earliest display technologies is the cathode ray (vacuum) tube (CRT), which displays an image by raster scanning an electron beam across a phosphor-coated glass screen [35]. Early cathode ray tube televisions were small, round, monochromatic displays with poor contrast, low screen luminance and low resolution, but over time they evolved into large rectangular, color displays (typically up to 40 inches in diagonal length) [36]. From the 1940s through to the 1980s, cathode

ray tube televisions were rapidly adopted in the home [37], with time spent watching television increasing from around 1 to 4 h per day over this period [38,39]. In the 1970s, with the advent of the personal computer, cathode ray tube displays were rapidly adopted in the workplace. With prolonged use of these displays, there was concern that this technology might have a negative impact on the user's health [40–43]. Although several studies concluded that cathode ray tube displays were not hazardous with respect to either emitting electromagnetic radiation [44,45] or chemical exposure [46], they did highlight possible issues relating to ergonomics and ocular symptoms [46,47]. Key issues with cathode ray tube technology related to veiling glare [48,49], reflections [50], limitations to resolution/pixel density [51] and the perception of flicker due to the relatively low refresh rate (50–60Hz) [52,53]. Newer cathode ray tube technologies introduced in the 1980s and 1990s looked to address these issues with the introduction of higher refresh rate monitors (75–120 Hz, see Section 2.2.6) [54], less curved screens [55,56], antireflective coatings/filters [57,58], more compact designs [59], and higher resolution displays [60,61]. Despite such developments, reports of ocular symptoms and poor ergonomics persisted [61–63]. In addition, cathode ray tube-based displays had several shortcomings relating to their large size/weight, high cost, poor energy efficiency and safety/environmental concerns, leading the industry to seek alternative display technologies [64], particularly for use in mobile devices [65].

2.1.2. Flatscreen display technology

2.1.2.1. Liquid crystal display (LCD). A key step in the development of low-powered, compact, and power-efficient displays was the introduction of liquid crystal-based screen technology in the late 1970s [66]. These displays typically comprise a liquid crystal layer, sandwiched between cross-polarized films. In its relaxed phase, the liquid crystal layer rotates the polarized light, resulting in the liquid crystal display stack transmitting light, whilst an applied voltage causes the liquid crystal to re-align and light to be blocked by the second polarizing film [67]. As the liquid crystal stack does not generate light, either a reflector or a backlight is placed behind the stack to produce a visible image. Liquid crystal displays can be segmented, where a limited number of individual digits or fixed symbols are displayed, or a pixel matrix, which is more suited to alphanumeric or variable graphics. Although often perceived as dated technology, monochromatic segmented displays are still widely used (e.g. watches and calculators) due to their low cost, low power consumption and high contrast even under bright lighting conditions. In the early 1980s, the development of matrix liquid crystal displays was key in allowing laptop computers to flourish [68]. These were initially reflective monochromatic displays, although the addition of a red-green-blue filter layer and a cold cathode fluorescent lamp backlight enabled the production of the first generation of color liquid crystal displays [69]. These early displays had limited resolution (typically 640 × 480 pixels), low screen refresh rate (typically 30 Hz), ghosting and poor contrast [70]. The incorporation of thin film transistors and capacitors directly onto the substrate allowed each pixel to be individually addressed in an efficient manner [71]. These active-matrix thin film transistor liquid crystal displays were a large step forward in technology, due to their higher resolutions, larger screen sizes, power efficiency, faster response times and higher refresh rates, becoming the standard for flatscreen technology up until the present day.

2.1.2.2. Backlight technology. Early liquid crystal displays used cold cathode fluorescent lamp backlighting, although in recent years there has been a shift to light-emitting diode (LED) backlighting, allowing displays to be lightweight, reliable, compact, long-life and energy efficient [72]. As light-emitting diodes are typically monochromatic, white light-emitting diodes make use of phosphors which partially convert the high energy emitted blue light into lower energy light [73]. Even with these phosphors, there is still a distinct spectral peak in the blue region (around 450 nm), along with additional peaks between 500 nm and 700 nm, corresponding to the light emitted by the phosphor coatings (Fig. 1). This white light (380 or 400–700 nm) is then filtered through red, blue, and green liquid crystal display subpixels to produce a wide range of colors [74]. Modern light-emitting diode backlights look to address the spectral imbalance with the use of enhanced phosphors [75] or quantum dot treatments [76] (nanoscopic particles which produce energetically equal green and red spectral peaks when excited by a blue light-emitting diode), to reduce blue light emission and improve color accuracy [77].

2.1.2.3. Organic light emitting diode (OLED) displays. High resolution organic light-emitting diode (OLED) displays are increasingly used in high-end electronic devices, such as televisions, smart watches, mobile phones, games consoles, digital cameras, tablets, and laptop displays. An organic light-emitting diode works in a similar way to an light-emitting diode, although it uses organic materials in the conductive and emissive layers. organic light-emitting diodes can produce either white light, which is then modified by red-green-blue filters, or separate red, green, and blue light-emitting organic light-emitting diodes [79]. Organic light-emitting diode displays are typically thinner, lighter, and more flexible (when manufactured on a flexible substrate) than a liquid crystal display, with a wide viewing angle, deep blacks, excellent contrast, highly responsive pixels and good color accuracy [80,81]. However, potential drawbacks of this technology include (i) permanent image retention (screen burn-in), (ii) organic molecule degradation with reduced light output over time [7], (iii) power consumption [82] (particularly with bright screen content), and (iv) the potential for subtle screen flicker due to pulse width modulation (rapidly turning the organic light-emitting diodes on and off to create the illusion of a dimmer display; Fig. 2) [83], potentially contributing to the reported eye strain and headaches [84]. Pulse width modulation dimming is not limited to organic light-emitting diode displays and is commonly observed with liquid crystal display screens; however, the frequency of flicker is typically lower in an organic light-emitting diode display (around 120–240 Hz versus 1000 + Hz) and is therefore potentially more problematic [85]. Although this rate of flicker is beyond the critical flicker fusion rate (50–90 Hz), it has been shown that, during saccadic eye movements, humans are able to perceive visual flicker artefacts at rates over 500Hz [86]. This pulse width modulation flicker is reported to be more pronounced when the screen is dimly lit, in low ambient light environments and at short viewing distances [87]. This observation is potentially more problematic in the young, as they generally have better vision and are more sensitive to subtle flicker at higher frequencies [88]. To address these concerns, screen manufacturers are currently developing technologies to reduce issues with pulse width modulation dimming using either a direct current dimming strategy or by increasing the pulse width modulation frequency to fall outside the range of concern [89]. It is frequently reported that organic light-emitting diode displays emit less blue light than light-emitting diode-backlit liquid crystal displays [90], however, a study comparing the two technologies found that blue light emission levels were essentially independent of the display technology, but were closely related to the correlated color temperature of the display [91].

2.1.2.4. Electronic paper (E-paper and E-readers). In the United States, around 1 in 5 people report owning an electronic paper e-reader [92], with around 20% of book sales made in this format [93]. E-readers are different from tablets and smartphones, with a display that consists of millions of microscopic fluid-filled microcapsules (~40 μm diameter), sandwiched between two transparent electrodes. Each microcapsule contains negatively charged black pigment and positively charged white pigment separated by a transparent fluid. A negative charge applied to the bottom electrode results in repulsion of the black particles upwards and a darkened area on the display, whereas a positive charge results in

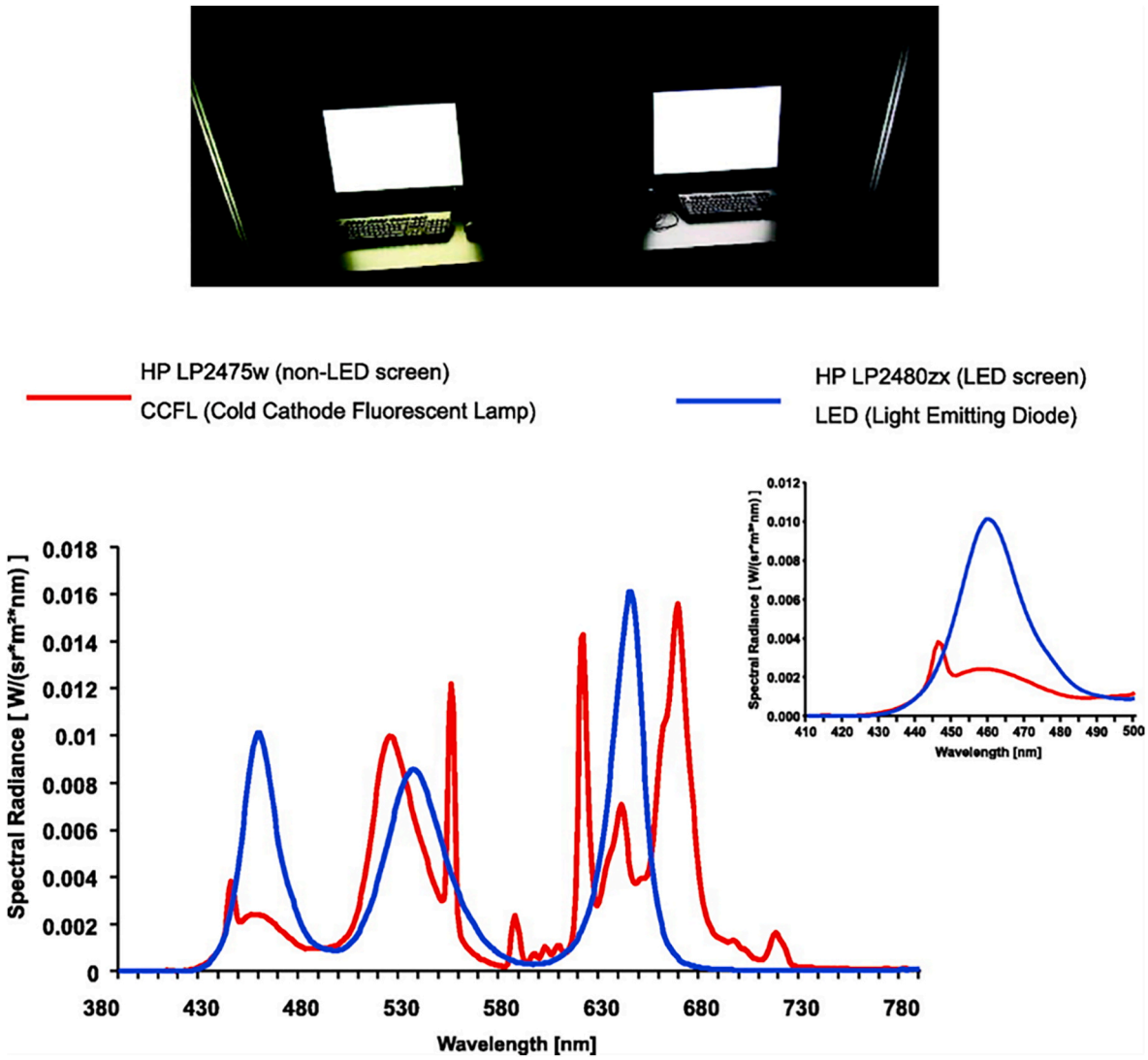

Fig. 1. Comparison of the spectral output of a cold cathode fluorescent lamp backlit thin film transistor (TFT) display (red line) with a light-emitting diode (LED) backlit TFT display (blue line) [78].

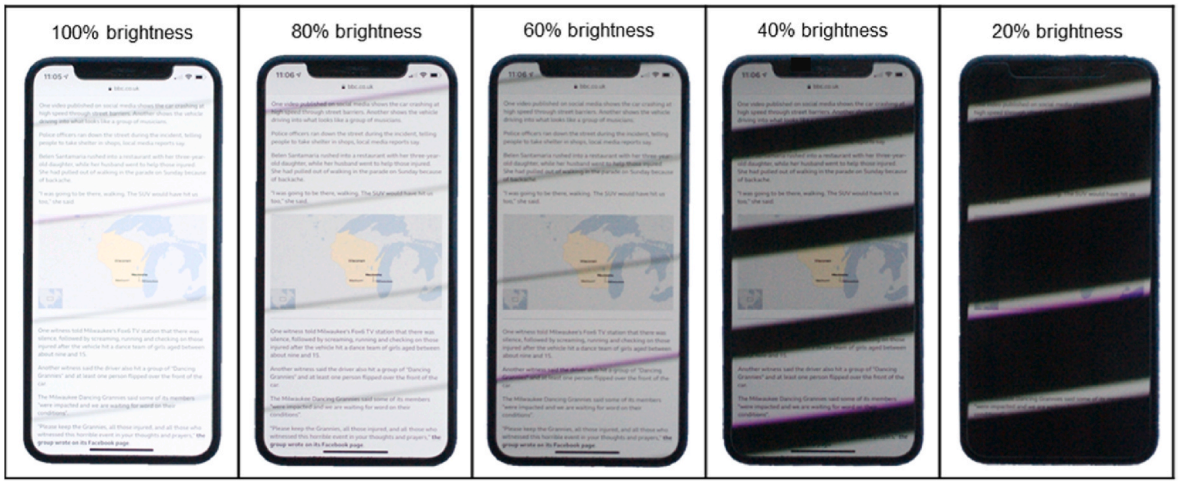

Fig. 2. Short exposure photographs (exposure: 1/8000 s) highlighting organic light-emitting diode pulse width modulation dimming on a smartphone screen.

a white appearance. E-paper displays are typically grayscale although a red-green-blue (RGB) filter can be applied, albeit with rather muted colors [94]. Alternative electronic paper (E-paper) technology uses bistable cholesteric liquid crystal display technology to produce a reflective display [95]. E-paper has very low power consumption (as power is only needed to refresh rather than maintain the display), low-glare and high contrast (closely mimicking real ink on paper), with no backlight required under normal lighting conditions as the display is reflective. However, as E-paper technology is expensive to manufacture and is typically slow to update, it is unsuitable for media requiring fast changing displays [94].

The typical viewing distance for an e-reader is around 30–60 cm [96–98], which is reportedly less than a for paper book but greater than for a phone [99], although it is known to vary with text size [96], ambient illumination [96,100] and user age [98]. This working distance is significantly less than that recommended for desktop monitors [101–106] and is likely associated with E-paper displays being hand-held, having a smaller screen size and lower luminance contrast than a liquid crystal display monitor. The letter contrast on e-reader displays is comparable with that of printed text [98,107], although this can be reduced by integrating lighting, touchscreen, or screen protector films [108]. Reading time, engagement, blink dynamics, eye movements, pupil size and legibility (reading behavior) are generally comparable between E-paper and printed paper [97,98,107,109]. The preferred viewing angle is similar to a tablet device at around 30°–40° [96], which may play a role in reducing corneal exposure [110]. Digital eye strain is typically less marked with E-paper compared to conventional, non-digital paper [84,97,109,110], although this is not always the case [111].

2.2. Digital display characteristics and use

2.2.1. Light emission

With the widespread adoption of organic light-emitting diode and light-emitting diode-backlit displays, concerns have been expressed regarding their short wavelength blue light emission [112] and the potential of such emissions to cause health issues [113–116]. It is well established that high intensity blue light can cause damage to the retina [3] and ocular surface [4], but current understanding is that the low intensity blue light produced by digital displays is insufficient to cause phototoxicity, even following prolonged periods of use [112]. There is, however, growing evidence that blue light exposure can suppress the production/release of melatonin [5,117–119], a hormone released by the pineal gland in the brain, that plays a crucial role in circadian rhythm entrainment [120]. Although all types of light can suppress melatonin [121], blue light has been found to shift circadian rhythm by twice as much (3 h) as green light (1.5 h) [122]. This is supported by research showing that a light-emitting diode-backlit liquid crystal display evoked a greater circadian melatonin response with associated behavioral changes, than a cold cathode fluorescent lamp backlit liquid crystal display (with a significantly lower blue light output) [78]. To address these concerns, digital device manufacturers have introduced blue-shifted liquid crystal displays [123] along with systems to modulate the display's short-wavelength output, depending on the time of day, to mimic natural spectral changes throughout the day (Fig. 3A) [124].

Some clinical studies have indicated benefits of low blue light output displays on melatonin levels/sleep suppression [125,126] and tear film stability [127], while others have shown no beneficial effect on melatonin levels [124] or sleep outcomes [128] when using 'night shift' mode technology. It has been suggested that brightness may be more important to melatonin suppression than spectral composition of the display [124] and that cognitive and psychological stimulation relating to screen use may play a role in sleep quality [128]. Given these conflicting findings, further research is needed to guide the development of next generation displays and control systems to optimize their spectral output and minimize their disturbance to the circadian rhythm and any potential impact on the ocular surface. This is particularly important given the known association between sleep quality and dry eye disease [129–133].

Another strategy designed to minimize the possible health impacts of blue light emission from a digital display is the implementation of dark/night mode [134]. Dark mode is a display setting which darkens the user interface, presenting light-colored text on a dark background (Fig. 3B), with the aim of reducing eye strain in low light environments [135], improving battery life on mobile organic light-emitting diode devices [136], minimizing the devices influence on the circadian rhythm/sleep [90] and enhancing aesthetics [137]. There is limited evidence on how these dark modes impact ocular health, comfort and vision, although positive polarity (black text on a white background) monitor displays typically result in improved legibility [138,139], a strong contraction of the pupil (resulting in greater depth of field, reduced blur and reduced

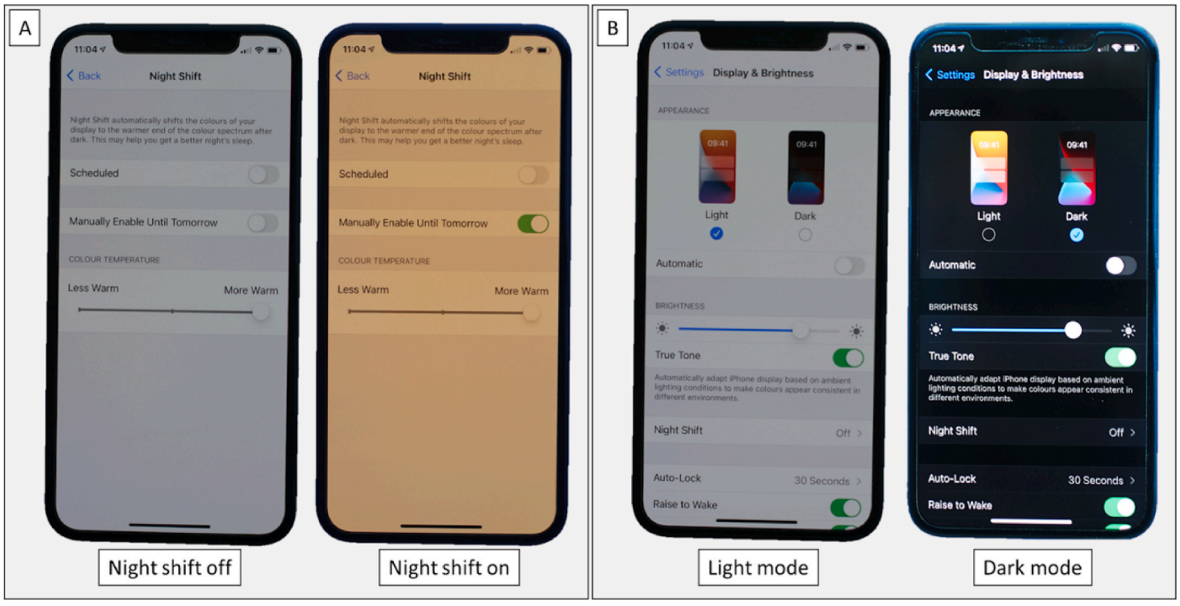

Fig. 3. (A) A comparison of a smartphone with its night shift mode disabled and enabled, and (B) with its Light mode and Dark mode display settings activated.

accommodative load) [140,141], improved visual acuity performance [138,142], reduced visibility of reflected light [143,144] and a greater subjective preference, [145] compared to negative polarity (white text on a black background) displays. However, several studies do appear to show a potential benefit of negative polarity, particularly in low ambient light conditions, where it has been suggested that screen brightness should mimic the surrounding light conditions, in order to minimize eye strain [21,146,147]. Lower visual fatigue scores, improved visual acuity and a preference for dark mode has been found in a virtual reality headset display [135], along with less blink suppression and faster pupil accommodation (objective metrics typically associated with reduced fatigue) for the negative polarity liquid crystal display mode viewing, although counterintuitively, subjective preference and visual fatigue data favored the positive polarity mode [148]. The effect of these display modes is known to be dependent on the display technology and the environment in which they are used [135,138], and thus further research is required to better understand the optimum display mode for specific devices over a range of lighting conditions, in order to maximise text legibility and minimize visual fatigue.

2.2.2. Screen size, position and resolution (Table 1)

Liquid crystal and organic light-emitting diode displays are available in a wide range of screen sizes from less than an inch to over 100 inches [149,150]. Over the last 20 years there has been a consistent trend for increasing screen size across a range of key display technologies, including computer monitors, televisions and mobile phones [151]. As screen size has increased, so too has the resolution of these displays [152,153], in part to maintain visual fidelity on these larger screens and, more recently, to produce screens which surpass the resolution limit of the human eye (so-called 'retina' displays) [154]. In particular, the size of the display is known to influence the recommended viewing distance advocated by the manufacturer, with a longer viewing distance for larger displays to reduce the need for excessive eye or neck movements during use [155]. To maximize screen size whilst maintaining the surface perpendicular to the user, curved screens have been introduced [156]. Research has highlighted that display size and resolution influences a wide range of variables including viewing distance [105,157,158], text legibility [159,160], accommodation [161], asthenopia [162], pupil size [163], musculoskeletal strain [164,165] and visual performance [166], although many of these effects are likely to be device specific. These larger high-resolution displays have been shown to aid productivity [167–171] and improve the ability to share content [172], but such displays typically have increased power demands, device weight/bulk and a requirement for more graphical processing power.

Display size is also known to influence gaze angle, with larger displays (e.g. televisions and large monitors) typically viewed at, or slightly below, primary gaze [173], whilst smaller handheld devices (such as smartphones and tablets) typically induce a larger downward gaze angle [174]. Increased downward gaze angle reduces the exposed ocular surface area [174] and may mitigate ocular dryness [175,176]. Angles of gaze that increase or widen the interpalpebral fissure increase the exposed ocular surface area, which can thin the lipid layer, alter the mucin layer, and reduce tear film stability [174,177–179]. A study found that the exposed ocular surface area when reading a book in the downward gaze position was 1.2 cm^2, but when reading on a computer was doubled and when reading with upward gaze, the ocular area exposed was almost tripled [178,179]. It has been reported that the effect of lowering the gaze angle by 25° significantly reduced the exposed ocular surface area during the active task, indicating that a low position of the monitor may be preferable [174]. Unlike the desktop monitor, when reading a book or when reading on a laptop, tablet, or smartphone, it is often read with the gaze position downwards, reducing the area of exposure of the ocular surface, and/or the need for blinking (see Section 6.1.1) [174,180,181].

2.2.3. Refresh rate (Table 1)

The refresh rate is the frequency at which a consecutive series of frames or images can appear on a display panel. In general, the faster the refresh rate, the smoother the image appears, with a low refresh rate risking a flickering or jerky image [182,183]. With cathode ray tube displays, as the electron beam rapidly scans the screen, the phosphor is momentarily excited before quickly fading until it is excited by the next raster beam scan. This results in much of the screen being dark at any one point in time, potentially resulting in the perception of flicker. Cathode ray tube televisions typically have a refresh rate of 50/60 Hz (Europe/United States) using an interlaced video format (raster scanning alternating scan lines) [184]. Although this was generally sufficient to avoid any perceived flicker or discomfort with television displays, with cathode ray tube monitors the lower-persistence phosphors, use of progressive scan (i.e. non-interlaced) and shorter working distance resulted in a perception of screen flicker for some users [185]. Successfully minimizing these shortcomings, high refresh rate cathode ray tube monitors and televisions were developed (typically between 75 Hz and 120Hz) [53]. In contrast, liquid crystal screens display the current frame until it is replaced by the next frame. This so-called 'sample and hold' approach reduces the incidence of flicker, but can result in significantly greater perceived motion blur [186]. Several techniques have been developed to address motion blur with liquid crystal displays, including motion interpolation [187], black frame insertion [188] and backlight strobing [189]. Although effective at maximizing image quality, some users appear sensitive to the associated flickering [190]. With liquid crystal displays, the typical refresh rate is 60 Hz, although to provide a smoother experience, particularly for dynamic content such as video games, higher refresh rate monitors (75–240 Hz) are now available [191]. The downside of a high refresh rate display is the graphical processing power required to maintain the desired refresh rate. Low-temperature polycrystalline oxide displays have an adaptive refresh rate which can reduce from 60 Hz to 1 Hz when not in use, to mitigate battery-life issues, whilst remaining in an 'always-on' configuration [192].

2.2.4. Viewing distance (Table 1)

Digital displays are integrated into a wide range of devices, with the distance between the display and the user's eyes ranging from 1 cm to many meters. The preferred viewing distance is influenced by (i) display characteristics (e.g. screen size [105,157,158], task type [104], display type [96], character size [96,193], screen luminance [158,194], screen color combination [106], reflections [144]), (ii) user characteristics (e.g. age [98,195,196], arm length [196], posture [197,198]) and (iii) environmental characteristics (e.g. workstation design [199], ambient illumination [96], frequency of breaks [106]). Viewing distance is known to influence a wide range of clinically relevant parameters including asthenopia [193], body/neck posture [198,200], light exposure from the display [194], accommodative/convergence demands [193], pupil size [201], ocular surface exposure [199], blinking characteristics [144,202,203], blurred vision [200] and ocular dryness symptoms [200]. Intuitively, the assumption is that a shorter working distance is to be avoided as it has the potential to increase accommodative/convergence stress [200], induce asthenopia [204] and act as a myopiagenic stimulus [205,206]; however, studies have also highlighted improved user performance and symptomatology with a shorter working distance when viewing a computer display [200].

2.2.5. Screen brightness & contrast

A range of technologies have been developed to optimize lighting output, including full-array local dimming [222], micro light-emitting diode backlighting [223] and quantum dot light-emitting diode/organic light-emitting diode displays [224,225]. These high dynamic range displays present an image with greater realism and depth, delivering improved subjective image quality when compared with conventional technology [226,227]. However, these high output displays also

have the potential to produce discomfort glare [228], which has been associated with a contraction of the muscles surrounding the eye [229], a reduction in palpebral fissure area, altered blink dynamics and asthenopia [230]. The sun has a brightness of around 1.6 billion cd/m^2 [231], so while digital display brightness has increased over time (typically around 250–2000 cd/m^2 for an liquid crystal display) [232], it is still orders of magnitude dimmer than many day-time real-world situations. With the trend for increasing screen brightness, further work is needed to understand how these displays can be optimized to maximize visual quality, whilst minimizing any negative impact on ocular surface health.

2.3. Virtual and augmented reality headsets

Although virtual reality devices have been around since the late 1970s, their uptake as consumer devices has only increased rapidly in recent years, with around 12.5 million units sold worldwide in 2021 [233]. A virtual reality headset is a head-mounted device which completely covers the eyes and provides a heads-up display capable of generating an immersive three-dimensional experience [234]. Virtual reality headsets typically comprise a stereoscopic digital display with associated optics, stereo sound, head-mounted tracking sensors and handheld controllers. The virtual reality system constantly updates the field of view of the display, based on head tracking sensors, to generate an immersive experience in the virtual environment [235]. Until recently, virtual reality systems have required a wired connection to a high-powered personal computer, however, all-in-one devices with inside out head tracking (externally facing headset cameras to track head position), in-built graphics processing and battery are increasingly popular in the consumer space due to their portability, low cost, and wireless setup [236]. To obtain a wide field-of-view, reduced headset bulk and minimal accommodative demand, a lens (or series of lenses) is required between the digital display and the user's eyes [237]. These lenses are designed with a focal distance of around 1–2 m [238–240], whilst minimizing distortion and chromatic aberrations. Although historically the field-of-view in virtual reality headsets has been severely limited [234], the latest head-mounted device designs allow a field-of-view approaching that of the human eye [241].

To provide a clear, and undistorted view, the virtual reality display needs to have (i) sufficiently high resolution to avoid pixilation, (ii) a high refresh rate (ideally >90 Hz) to ensure the display is accurately reflecting the intended view of the user, and (iii) a response time that is sufficient to transition rapidly from frame-to-frame. A key challenge with existing virtual reality technology is that the angular resolution of the displays currently falls well short of the resolution limit of the human eye [242], and even if displays were able to meet this required resolution (around 6000 pixel monocular resolution) the graphical processing power required would be prohibitive [242]. A possible solution is to use a foveated rendering approach, which tracks the user's eye movements and provides high resolution rendering in the region of the display relating to the fovea, whilst rendering a degraded resolution across the remainder of the screen (associated with the retinal periphery) [243].

Given the rapid increase in the use of virtual reality devices, a wide range of scientific research has been undertaken highlighting a number of health-related issues, including vergence-accommodation conflict (mismatching cues between the distance of an object and the focusing distance) [244], virtual motion sickness (also known as cybersickness - a result of conflict between observed and sensed motion) [244,245], impact on binocular vision [246], weight/comfort of the device (including neck/back strain) [150], risk of falls and altered mobility [247–249].

A virtual reality headset sits near the user's eyes and creates an isolated environment that has the potential to influence the ocular surface and tear film due to increasing atmospheric temperature (around +10 °C) and ocular surface temperature (around +0.5 °C), although counterintuitively a small reduction in humidity has been found over a 40-min wearing period [250]. When compared with a conventional display, virtual reality headset wear has been reported to result in a clinically significant improvement in lipid layer grade and tear film stability, thought to be associated with shielding from the surrounding environment and the warmer temperature at the ocular surface promoting meibum secretion [250,251]. However, another study found no significant change in tear film stability or meniscus height following virtual reality headset wear, with comparable observations following laptop use [252]. Whether use impacts blinking characteristics is currently unclear [251,253], although deeper virtual reality immersion [254] and cybersickness [255,256] increase blink rate. Several studies have indicated that virtual reality headsets can improve clinical tear film signs [250–252], and this may even potentially be useful as an environmental modification for treating dry eye diseases, although this has not yet been specifically investigated.

An augmented reality headset is a head-mounted device that overlays computer generated virtual objects onto the wearer's real-world view [257]. In its simplest form, this device can be a head-up display, such as the Google Glass, where a small digital display is viewed indirectly through a semi-silvered prism mounted on a spectacle frame [258]. More complex true augmented reality systems, such as the Microsoft HoloLens and Magic Leap augmented reality headsets, map the real-world using 3-dimension room scanning technology (typically using headset-mounted infrared projection systems) in combination with 3-dimensional headset tracking to ensure the system can align virtual objects with objects in the real-world. A wide range of optical technologies have been proposed for augmented reality headset displays, including holographic, diffractive and reflective waveguides [242]. To allow the computer-generated image to be easily viewed when overlaid on the real-world, a tinted lens/shield is often used to subdue real-world lighting. Although augmented reality headset technology has been commercially available for a number of years, these systems have typically been focused on enterprise solutions, primarily due to their high cost, display limitations (low refresh rate/high latency/limited field-of-view/poor outdoor performance), headset weight/bulk and challenges with rapidly mapping the surrounding environment [257], in addition to more general concerns relating to safety associated with reality modifications [257] and privacy concerns [259]. There have also been reports in the literature relating to motion sickness-like symptoms [260], thought to be caused by multiple factors including (i) visual-vestibular mismatch and (ii) display characteristics such as low frame rate and higher field-of-view [261]. While evidence from virtual reality headset research generally highlights no significant short-term clinical effects following headset use in the adolescent eye, no studies have investigated the longterm impact of augmented reality headset wear and thus further research is required.

3. The ocular challenges of a digital environment

The technological digital revolution has enhanced communication, increased access to information and enabled greater mobility. In the past, computing technology, from mainframes, was only available to few people, whereas handheld devices are now available to most of the world's population. Hence, the tasks people routinely conduct have substantially altered, making a direct comparison with non-digital technology difficult, but there are some specific features of the digital environment (as described in Section 2) that can challenge the ocular surface.

3.1. Display resolution and refresh rate

Lower screen resolution can affect reaction times and fixation durations [166]. Initial concerns regarding poor quality displays [21] have largely been overcome. Nevertheless, a recent survey found that poor screen resolution was associated with reported ocular symptoms as was a closer working distance [262]. Few near monitors can yet achieve the

resolution of 0.092 mm pixel separation recommended for accurately displaying images without aliasing [263]. Working distance is usually shorter with a mobile phone than with a typical paper task [210]. Studies have shown that the screen refresh rate might affect accommodation, blink rate and reading speed [264], but not saccadic eye movements [265].

3.2. Device dimensions/type

Screen curvature affects visual fatigue, with a curvature of about 600 mm being optimal [156]. Larger screen size and three-dimensional imagery both increase search time [160] and visual stress [266]. Despite the smaller size, a comparison of a similar task on a personal digital assistant, an e-book reader and a notebook computer found visual fatigue was significantly greater when participants read from the personal digital assistant compared with the other two displays, although reading speed and accuracy rate were similar [267].

3.3. Screen lighting and reflections

External lighting can adversely affect a digital user's visual comfort, as well as oculomotor function and task legibility. Luminance of the surrounding visual field influences the amplitude of accommodation and symptoms of eye strain [262,268]. Lighting of the screen can also impact work efficiency and visual comfort [269]. Screen reflections result in a shorter and more variable viewing distance and cause visual fatigue [270], similar to E-paper [271].

3.4. Human factors

Digital devices are often positioned differently to non-digital similar tasks (see Section 2.2.5), which can result in eye strain [262]. Longer screen time have been found to cause more severe dryness symptoms [272], although this metric fails to capture the passive or cognitively demanding nature of the task. Reading smaller text also increases visual fatigue [159,160,273].

4. Epidemiology

Studies have examined the prevalence of digital eye strain in various countries (Table 2). A global prevalence of digital eye strain was estimated to be 70.7%, but ranged widely from 31.9% in bank workers in Italy [274] to 97.3% in university students in Saudi Arabia [275]. These numbers highlight the high prevalence of digital eye strain across the world and the importance of its global impact. However, the wide range for digital eye strain prevalence partly reflects the current lack of a unified definition and agreement on diagnostic criteria for the condition (see Section 5).

Most studies on the worldwide prevalence of digital eye strain rely solely on subjective responses to questionnaires, distributed electronically via email or social media, which in itself may lead to selection bias. In addition, most questionnaires are custom made and list various symptoms relating to proposed digital eye strain reported in prior studies, asking for their presence, frequency, intensity, or for information on all three aspects. These survey questionnaires are usually translated into the country's main spoken language by the authors, lacking validation and not accounting for cultural perceptions. As a result, digital eye strain is then diagnosed inconsistently across these studies, often based on the presence of a single symptom, occasionally restricted to a certain frequency or intensity, and reported as the prevalence in a certain region and demographic. This diversity in reporting between studies makes it difficult to compare digital eye strain prevalence across countries.

The Computer Vision Syndrome Questionnaire (CVS-Q) is currently the most widely used questionnaire that is validated and specifically designed for the diagnosis of digital eye strain [276]. It has been used to determine the prevalence of digital eye strain in 12 studies included in Table 2. Four of these studies were conducted in Spain, which is unsurprising as the questionnaire was developed there, and the original version is in Spanish. The data appear to suggest that digital eye strain is more prevalent in university students [277] and presbyopic computer terminal operators (76.6% and 74.3%, respectively) [278], compared to healthcare [279] and office workers (56.9% and 51.0%, respectively) in Spain [280]. However, these results require careful interpretation. Many of the symptoms that are surveyed in the CVS-Q overlap with symptoms of dry eye disease, such as burning, foreign body sensation, tearing, eye redness, eye pain and dryness. As such, the many confounding factors that apply to dry eye disease would also impact the CVS-Q score, as would ocular allergy (itching symptoms) and infection which can cause similar symptoms. In addition, age, contact lens wear, systemic comorbidities and environmental factors are not always accounted for in these epidemiologic studies [281].

In a large population-based study investigating the association between those with eye dryness symptoms and occupation, professionals and clerical support workers were found to have a higher risk of dry eye compared to other occupations. This increased risk, however, was no longer apparent after correcting for 45 dry eye associated comorbidities, with contact lens wear being the most important confounder, followed by systemic comorbidities. After correction for dry eye-associated comorbidities and traits, building workers and metal and machinery workers showed the highest risk of symptomatic dry eye, perhaps highlighting the impact of exposure to dust, chemicals and toxins, as well as climatic influences on the development of dryness symptoms [282].

The limitations in population sample selection, heterogeneity in digital eye strain diagnostic criteria, lack of control of various variables, and cultural/linguistic factors, all explain a large amount of the

Table 1
Typical display size, resolution (horizontal x vertical pixels), refresh rate and viewing distance for a range of digital display devices. No publications on digital signage and eye strain were identified. Note: 1080p = 1920 × 1080 pixels, while 4 k = 3840 × 2160 pixels.

Digital device	Diagonal size (inches)	Resolution (pixels)	Refresh rate (Hz)	Viewing distance (cm)
Smart watch	1–2	320 × 320–448 × 368	1–60	20 - 40 [165,207]
Virtual reality headset	3–6	1440 × 1280–3840 × 2160	60–120	Actual 3–6 (apparent viewing distance = 100–200) [208]
Handheld console	3–7	240 × 160–1280 × 720	50–60	15 - 35 [209]
Smartphone	4–7	1334 × 750–2778 × 1284	60–120	20 - 50 [157,194,196–198,204,210–212]
E-reader	6–10	600 × 800–1072 × 1448	n/a	30 - 60 [96,157,195,213,214]
Tablet	5–13	800 × 600–2732 × 2048	60–120	30 - 60 [193,213,215,216]
Laptop	10–17	1920 × 1080–3840 × 2160	60–120	35 - 70 [144,199]
Computer monitor	19–32	1920 × 1080–3840 × 2160	60–240	45 - 80 [101–106]
Television	19–105	640 - 480–3840 x 2160	60–120	150 -600 [101,158,217–221]
Paper book	7–13	n/a	n/a	25 - 55 [101,157,213]

Table 2
Global prevalence of *symptomatic* digital eye strain OR computer vision syndrome.

Country	Reference	Population	N =	Diagnostic criteria	Prevalence (%)
Brazil	[283]	Call center operators	476	Custom Survey	54.6
China	[284]	School students (6–18 years)	2005	CVS-Q	77.0
	[285]	Medical students	137	CVS-Q	63.5
Egypt	[262]	Medical students	733	CVS-F3	87.9
	[286]	Information Technology professionals	108	CVS-Q	82.4
Ethiopia	[287]	Bank workers	304	Custom Survey	73.0
	[288]	Computer terminal operators	607	Custom Survey	69.5
	[289]	Secretaries working in ministry offices	455	Custom Survey	68.8
	[11]	University instructors	416	Custom Survey	70.4
	[290]	Bank workers	359	Custom Survey	74.6
Ghana	[291]	University administrative staff	200	CVS-Q	51.5
	[292]	Bank workers	139	Unclear	71.2
Italy	[274]	Bank workers	212	Custom Survey	31.9
	[293]	Computer terminal operators	190	Custom Survey	46.2
India	[294]	Computer terminal operators	419	Custom Survey	46.3
	[295]	Medical and Engineering Students	416	Custom Survey	80.3
	[296]	Medical and engineering students	236	Custom Survey	71.6
	[297]	Medical students	463	Custom Survey	77.5
	[298]	Adults	407	Custom Survey	90.4
	[299]	Children	217	CVS-Q	50.2
	[300]	School children (5–18 years of age)	654	CVSS17	92.8
	[301]	Adult students of online classes, teachers of online classes, and general population	941	CVS-Q	50.6 in students 33.2 in general public
Japan	[302]	Computer terminal operators	561	Custom Survey (Dry Eye)	76.5
	[303]	Computer terminal operators	369	Custom Survey	59.1
Jordan	[304]	University students	382	CVS-Q	94.5
Jamaica	[176]	Undergraduate university students	409	Custom Survey	67.0 ([a]eye strain complaint)
Korea	[305]	Adolescent participants (14–18 years)	715	Custom Survey	63.6 [b]
Malaysia	[306]	University students	795	Custom Survey	89.9
Mexico	[307]	Office workers	108	CVSS17	93.5 (excluding CVS level 1)
Nepal	[308]	IT Workers	263	Custom Survey	82.5
	[309]	Patients presenting to ophthalmology clinic	70	Custom Survey	95.7
Peru	[310]	University graduate students	106	CVS-Q	62.3
Romania	[311]	Medical students	420	Custom Survey	86.1 ([a]most common complaint: tired eyes/eye strain)
Saudi Arabia	[312]	Medical students	634	Custom Survey	72.4
	[313]	Medical students	713	Custom Survey	51.5 (dry eye)
	[275]	University health sciences students	334	Custom Survey	97.3
	[314]	Radiologists	198	Custom Survey	50.5
	[315]	Adults	690	Custom Survey	77.6
	[316]	Adults	1939	Custom Survey	78
	[317]	Medical staff		Custom Survey	81.2
Spain	[280]	Office workers	426	CVS-Q	51.0
	[318]	Video display unit users with flat-panel displays	116	Customer survey [319]	72
	[279]	Healthcare workers	343	CVS-Q	56.9
	[278]	Presbyopic computer terminal operators	109	CVS-Q	74.3
	[320]	Adults	730	Custom Survey	66.6
	[277]	University students	244	CVS-Q	76.6
Sri Lanka	[321]	Computer terminal operators	2210	Custom Survey	67.4
United Arab Emirates	[28]	Medical students	471	Custom Survey	43.9 ([a]most common complaint)
USA	[322]	Patients attending optometry clinics	324	Custom Survey	65.0 ([a]most common symptom: eyestrain)
	[29]	Office workers	520	Custom Survey [319]	40.0 ([a]most common symptom: tired eyes)
	[319]	Office workers	638	Custom Survey	77.0 ([a]most common symptom: tired eyes)
	[23]	University students	729	Custom Survey	91.3

Computer Vision Syndrome Questionnaire (CVS-Q) [276]; Computer-Vision Symptom Scale (CVSS17) [323]; Computer Vision Syndrome: Form 3 (CVS–F3) [262].
[a] *Symptomatic*: asthenopia (eyestrain, eye fatigue, discomfort, tired and sore eyes), ocular surface related (dry eye disease, watery eyes, contact lens related), visual problems (diplopia, blurred vision) and extra ocular or musculoskeletal (wrist, neck, shoulder and arms).
[b] Ocular symptom score of 3 or more.

variability in the reported prevalence of digital eye strain around the world and limits the ability to compare prevalence between different countries. The unified definition and diagnostic criteria proposed in this report will help standardize and improve the quality of future epidemiological studies.

5. Diagnosis

Adopting the definition of "Digital Eye Strain describes the development or exacerbation of recurrent ocular signs and/or symptoms related specifically to digital device viewing" (see Section 1), a diagnosis should be able to differentiate a change in symptoms and/or signs, that occur in a digital, but not in an equivalent non-digital, environment conducted for the same duration that exceeds the noise of repeated measures [324]. As such, these symptoms/signs will decrease when digital device use is ceased and the condition is not due to pathology, but could damage the ocular surface if left unmanaged. While dry eye disease and binocular vision problems are associated with digital display use, it is not always clear from studies whether participants would also have reported similar symptoms or displayed signs, for a non-digital task

of similar intensity and duration. It should be noted that the impact of digital devices on dryness signs and symptoms can differ in the same individual conducting similar tasks [110].

As highlighted in Section 4, previous attempts to diagnose digital eye strain based on symptomology have largely used unvalidated questionnaires such as the Computer Vision Syndrome: Form 3 (CVS–F3) [262], and/or been based on the occurrence frequency of symptoms [262,274,325], their intensity [326] or both [276,327,328]. Typical symptoms include eye burning, eye pain, headache, eye redness, photophobia, tearing, repeated/frequent blinking, heavy eyelids, ocular itching, blurred vision at distance and near, double vision, eyestrain and ocular foreign body sensation. As only one symptom is required, a prevalence of up to 97% has been reported (see Table 2). The digital eye strain questionnaire (CVS-Q) was refined using Rasch analysis, included 16 symptoms associated with digital eye strain and scored both the frequency and severity (each on a 0–2 scale), multiplied together and summed for a total score out of 36, with a cut off value of ≥6 (sensitivity 75.0% and specificity 70.2%) [276]. A more recent study confirmed this and reported a sensitivity of 80.0% and specificity of 83.1% using a cut-off of ≥7 [329]. The Computer-Vision Symptom Scale (CVSS17) [323] has also been refined and scaled by Rasch analysis and consists of 17 items exploring 15 different symptoms, but with two to four response categories. While both the CSV-Q and CVSS17 questionnaires were found to have acceptable psychometric properties, neither explored symptoms with non-digital tasks and both were limited by having no gold standard for comparison; the former arbitrarily chose the occurrence of at least one symptom, two or three times a week and the latter correlated the findings with a visual discomfort questionnaire.

Besides symptoms, some researchers have required clinical signs as part of their diagnostic criteria, such as visual acuity measurement, refractive error and objective accommodation [330], conjunctival hyperemia and/or multifocal electroretinogram abnormalities [262]. However, these criteria are vague and no cut-off values or algorithm to combine the stated metrics have been articulated. Several papers have proposed diagnostic signs for digital eye strain [331]. Critical flicker fusion frequency was the only visual function parameter that decreased significantly after a digital visual task, but a similar non-digital task was not examined [331]. A more recent study was unable to support critical flicker frequency as an objective measure of eyestrain related to digital devices [332]. While blink rate decreases with digital tasks [333], a carefully controlled study demonstrated this was also the case with a similar cognitive intensity paper task [25]. Modern soft contact lens wear has not been found to increase digital eye strain symptom frequency or severity [23]. Orbicularis oculi blood flow, but not load, has been found to be related to eye pain in a digital environment [24]. Accommodative facility has been found to be reduced in individuals with digital eye strain [334]. Intensive, compared to less frequent, computer users generally have greater symptomology, staining, tear instability, meibomian gland drop out and goblet cell loss, although a similar tear volume [307,335,336]. However, none of these studies provide strong evidence that any of these signs are diagnostic.

Therefore, currently, there is no robust algorithm to diagnose digital eye strain and many people ‘diagnosed’ with digital eye strain probably have dry eye disease, uncorrected/only partially corrected refractive error and/or a binocular vision anomaly, each of which have their own diagnostic criteria and established evidence-based management strategies. To diagnose digital eye strain, the individual must report the development or exacerbation of ocular symptoms (and possibly signs such as slower focusing) related specifically to digital device use, such as during reading a document. Until further evidence is available, confirming with a patient that they develop, or have an increase in, ocular symptoms or signs during digital device use, in a manner that does not occur to the same extent with an equivalent non-digital task, is required.

6. Effects/mechanism of action

The symptoms of digital eye strain are transitory and non sight-threatening, but they produce significant, chronic and frequent discomfort that can affect quality of life and reduce work and school performance (see Section 7). The symptoms and signs associated with digital eye strain specific to the eye can be broadly divided into those related to the ocular surface and the development of dryness symptoms, and those associated with visual and accommodative alterations associated with uncorrected refractive errors, reduced accommodation and oculomotor anomalies such as poor convergence, fixation disparities or uncompensated phorias. In addition, there are extraocular symptoms associated with ergonomics such as back, neck, and shoulder pain [16,22,29,337,338]. Symptoms related to the ocular surface and dry eye disease include a foreign body sensation, burning, dryness, irritation, tearing, blurred vision, sensitivity to light, glare and headache. Visual symptoms include blurry vision either at distance, intermediate or near, slowness of focus change, diplopia, eye strain, sensitivity to light, discomfort, fatigue, tiredness or weakness of the eyes, tearing, headache and sleepiness while performing a visual task [16,22,29,337–341]. Blurred vision after computer use, and refocusing difficulties are more closely associated with visual alterations and accommodation, with the sensation of tired eyes, eye strain, discomfort, irritated eyes, dryness, more associated with ocular surface alterations and dry eye disease [29]. These symptoms characteristic of dry eye disease and accommodative alterations can develop or worsen when using digital devices [22,29,337,342].

Exposure to digital devices and risk of developing digital eye strain, is reflective of the spectrum of daily technology-focused activities in modern life; social and work activities often involve the use of smartphones [27,82,339,342], and most work environments require regular use of digital displays such as a desktop or laptop computer in an office environment, teleworking or a combination of home-office working [29,110,307,336,343–345]. Device use is pervasive in modern classrooms, whether delivered as online schooling or as conventional on-site education [285,299–301,346–348]. Digital devices are becoming increasingly essential to reading tasks (such as tablets or e-readers) [109], and are frequently a mechanism for entertainment with videogames [27,349], among others. Exposure to digital devices occurs in both sexes and in any age group from children [27,299,300,346–348], to university students [275,285,301], to adults of working-age [29,302,307,336,339,344] and the elderly [343]. Each activity and age presents individual challenges in the use of digital devices and the subsequent presence and severity of digital eye strain.

Digital eye strain, symptoms can occur as early as 20 min after initiating digital device use [350]. Studies have reported the development of digital eye strain at 1 h [346], 2 h [351], 4 h [336,340,342], 5 h [299,313], and after one working day [302,352]. A study found an increased risk for dryness symptoms in computer workers using a computer for more than 8 h per day (odds ratio = 1.94; 95% confidence interval (CI), 1.22–3.09) [302]. The increase in digital eye strain seems to be proportional to the increase in daily hours of digital device use [29,299,301,302,313,340,342,346].

Other studies have found that 4 or 5 h reported use of digital device use might be a critical time for digital eye strain development. A study found that 4 h of continuous smartphone use could be a critical duration of screen time to induce digital eye strain since a significant increase in symptoms as measured using the Ocular Surface Disease Index (OSDI) questionnaire was observed, as well as a significant decrease in non-invasive tear breakup time, and increased tissue oxidative stress marker hexanoyl lysine in the tear film and reactive oxygen species on the ocular surface [342]. Similarly, a study found that more than 4 h of daily computer exposure resulted in lower tear breakup time and increased Ocular Surface Disease Index-assessed symptoms, corneal staining, and meibomian gland loss [336]. University students using digital devices for more than 4 h a day [340], or more than 5 h a day

[313] had an increased risk of developing digital eye strain symptoms (odds ratio = 1.52; 95% CI: 1.07, 2.16), such as headache (66%), dryness symptoms (51%), and blurred vision (44%) [313]. A multivariate analysis of school children found that using a digital device >5 h a day was an independent risk factor for digital eye strain [299]. A cumulative effect was also noted with increasing severity and/or prevalence of digital eye strain after more years of working with digital devices [307, 353]. Similarly, longer, more persistent and higher cumulative lifetime use of smartphones have been associated with increased prevalence of ocular symptoms [305].

6.1. Physiological mechanisms of action for the development of digital eye strain

The principal mechanisms implicated in the development of digital eye strain are: (i) blinking abnormalities that induce ocular surface and tear film alterations; (ii) underlying deficiencies in vision/accommodation/oculomotor function that induce visual disturbances of blurred vision, asthenopia, focusing and accommodative difficulties, fixation disparities, vergence anomalies and poor convergence; and (iii) extraocular alterations such as ergonomics and lighting. In addition to these, there are inciting and exacerbating factors that also may contribute to the development of digital eye strain (Fig. 4) [16,22,337].

6.1.1. Blinking abnormalities and ocular surface exposure

When using digital devices, people demonstrate blinking abnormalities and a higher risk of ocular surface exposure, including reduced blink rate, incomplete blinking and a greater gaze angle. These alterations can induce changes in the ocular surface and dryness symptoms [354]. Blinking is essential to maintain the homeostasis of the ocular surface keeping it moist and hydrated, minimizing corneal exposure, assisting tear drainage, reducing the accumulation of inflammatory mediators in the tear prism, and aiding in the distribution of mucins and meibomian gland secretions to promote maintenance of tear film stability [355–358].

Reduced blink rate generates instability of the tear film, which can promote the development of dryness symptoms [21]. Reduced blink rate has been reported in digital devices users as compared with hard-copy text users [178,359–362]. A study found a reduced blink rate of 3.6 blinks/min when reading on a computer screen as compared to 18.4 blinks/min when at rest before using the computer [360]. Another study compared the blink rate while reading and found a reduced blink rate in office workers of only 7 blinks/min when reading on a computer screen, compared to 22 blinks/min when relaxed, or 10 blinks/min when reading a book [178]. However, reading for 20 min on a computer screen versus a hard-copy text that was matched for the text size, contrast and of similar luminance and viewing angle, resulted in no difference in blink rate between the two media types [25], indicating that differences in the cognitive demands may be more important than the medium in determining a reduction in blink rate; however incomplete blinking was higher when reading on digital devices [25,363]. Another study in office workers found a reduced Schirmer test result that was more evident when the screen time was increased [364]. Blink rate can also be reduced when the image or the font are of low-resolution [365], when the font size is small, when the image is of low contrast or when there is increased glare [230,333]. Unlike that found with computers [25], studies have found that the blink rate is reduced when using a tablet (with a smaller digital screen) compared to a printed page even when the characteristics of text size, working distance, and the number of pages read are matched [109,180].

It has been suggested that digital eye strain is more likely to be caused by incomplete blinks than a reduction in blink rate [363]. Incomplete blinking is also associated with digital eye strain [25,333, 346,363]. The mechanism is thought to begin with a poor distribution of tears across the ocular surface, particularly in the lower third of the cornea. This incomplete distribution of the tear film produces alterations in the mucin and thinning of the lipid layer and accumulation of inflammatory mediators due to the reduced tear clearance and these changes cause tear instability and corneal erosions [174,180,333,350, 358,360,361,366–368]. Reading from digital devices (either computer or hand-held devices) induces higher percentages of incomplete blinking than reading from hard-copy text [25,180,346,366]. A study found that reading from a computer, tablet or hard-copy text all produced a reduction in blink rate, however digital devices produced a significantly greater increase in the rate of incomplete blinking than noted when reading from hard-copy text (14.5% vs 5% respectively) [180]. A study on young adults reading from smartphones found that the number of incomplete blinks per minute increased from a median of 6 times during the first minute to 15 times at 60 min [346].

An important factor in the development of digital eye strain is the level of cognitive and visual demand required to perform the task as well as the rate at which visual information is presented [350]. Activities that require high cognitive demands and high visual demands such as videogames or materials that are difficult to read or understand reduce the blink rate, because they require longer fixation times to be able to perform the task [333,350,369]. A study simulated office conditions to compare passive reading with active reading and writing activities on the computer and found that blink rate during the active task was 69% lower than with passive tasks; after the active test ended, a compensatory period of high blink rate occurred, stressing that interchange of work tasks with different cognitive demands might be important in controlling digital eye strain [174]. As with reduced blink rate, an increase in the rate of incomplete blinking may be a subconscious mechanism used to try to stay focused on the task, avoiding interruptions by suppressing spontaneous normal blinking [25,180,350,367,370].

6.1.2. Alterations in the ocular surface and tear film

Many typical digital eye strain symptoms have been associated with ocular surface and tear film alterations such as tear film instability, enhanced tear evaporation rate, reduced aqueous tear production and volume, meibomian gland dysfunction, alterations to the tear film lipid and mucin layers, corneal and conjunctival staining, ocular bulbar redness, tear hyperosmolarity and increased inflammatory markers [342,343,352]. However, it is common to find discrepancies in the findings between studies and between different digital devices, which may be attributed to the device type (see Section 2.1), ergonomics and task cognitive demand. It seems in general that computer use might induce more symptoms and signs than smartphone use [110,174,177, 339,342,343,350].

The tear film aqueous can be altered by digital device use, with a reduction in tear production (confirmed with the Schirmer test and tear meniscus height) [342,352,353,364]. The odds of having a reduced Schirmer test were higher in individuals with a greater total years working with computers (4 years versus 8–12 years odds ratio: 2.49, 95% CI: 1.02–6.55, and >12 years odds ratio: 3.61, 95% CI: 1.39–10.26) and longer hours per day spent working with computers (<2 versus >8 h odds ratio: 4.27, 95% CI: 1.47–13.66; adjusted for age and sex) [110, 353]. However, there are conflicting findings with some studies failing to demonstrate an association between total cumulative exposure time to digital devices and Schirmer test results [307], or no alterations in tear meniscus height after reading for 1–4 h from a smartphones and computers [336,342,346], or no significant differences in tear meniscus height and Schirmer test results after reading using paper versus a tablet [111,371].

Tear film stability has been found to be reduced with digital tasks [110,302,307,336,342,350,352,368,372]. One study reported that 97% of computer users had poor tear film stability (tear breakup time <10s) [307], while another reported 78% (<5s) [302]. Significant reductions in tear film stability were found with daily computer use >4 h versus those using the computer <4 h [336]. In addition, the cumulative effect of total exposure time to a computer was negatively correlated with tear film stability [307,336]. Reduction in tear film stability has been

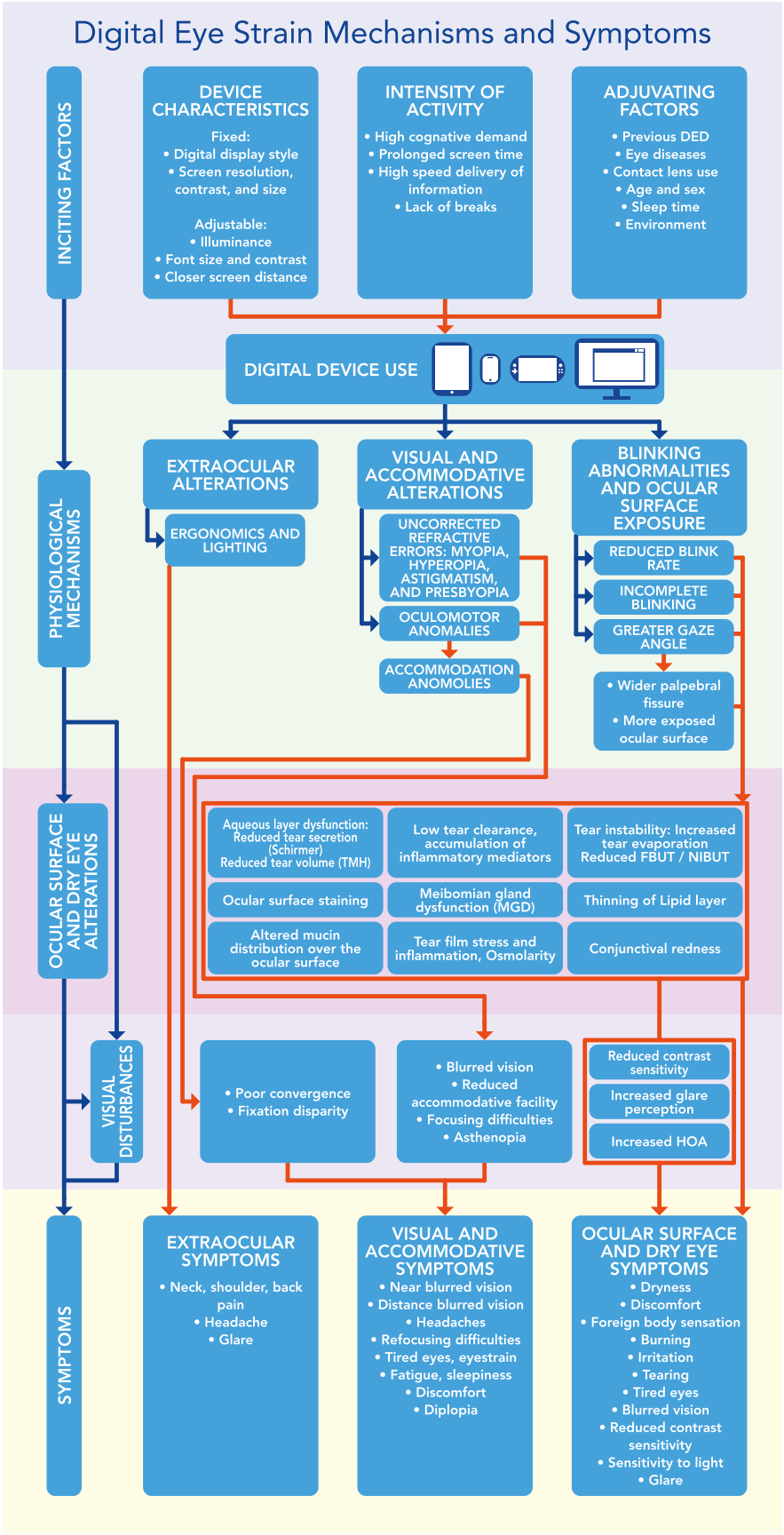

Fig. 4. Proposed mechanisms and symptoms of digital eye strain.

reported after 20–30 min of playing videogames [350,368], after using computers for 4 h [336], tablets for 20–60 min [111,154] and after 4 h of smartphone use [342,373]. However, several studies have found no impact of smartphone use on tear film stability [110,346,374]. No studies have systematically tracked the time course of when symptoms first occur and how this varies between individuals.

The impact of digital eye strain on the corneal and conjunctival epithelium can be assessed through ocular surface staining [302,336,372]. Computer workers generally have more ocular surface staining than non-computer users [372], particularly those working an average of 7.9 h daily [302] or >4 h daily [336] and this has been correlated with cumulative total screen time exposure [307]. The blink pattern and rate of incomplete blinks have been correlated with the presence and magnitude of corneal staining [367]. However, several investigations have not found increases in ocular staining with digital display use [375,376], which may be due to less cumulative exposure, as staining is considered a sign of more severe dry eye disease [377].

The prevalence of meibomian gland dysfunction can be increased in digital device users [21,336]. Long-term computer workers (mean 8 h/day, 8 years of use) had more severe meibomian gland dysfunction and gland loss than short-term computer workers (mean 3 h s/day, 5 years of use) [336], perhaps due to the effect on blinking leading to significantly greater chronic meibomian gland damage with gland obstruction, reduced expressibility, altered meibum quality, and subsequent atrophy of the glands [354,378].

The tear lipid and mucin layers might also be affected by digital device use, but there is limited evidence available. Thinning of the lipid layer occurs with eccentric gaze and the resulting greater exposed ocular surface area that can occur with computer use [177]. However, some authors do not find alterations in the lipid layer after performing a task on a computer [353], or a smartphone [346]. A study on digital display users found that mucin 5AC (MUC5AC) concentration in the tear film was reduced in those who used a computer for more hours daily (>7 h compared to <5 h) [345].

Inflammation and stress biomarkers have been found on the ocular surface and in the tear film of digital device users. Significant increases in tear film osmolarity have been reported after digital display use [110,343,352,379]. Increased tissue oxidative stress marker hexanoyl lysine and reactive oxygen species have been detected on the ocular surface after 4 h of smartphone use [342]. Significantly higher levels of interleukin-1β and interleukin-6 have been measured in computer workers compared with non-computer workers [343]. An increase in conjunctival bulbar redness after 15 min of reading on a computer device [380] and a smartphone [110], more limbal and lid redness in digital display users (>4 h daily) [381] and increased risk of ocular redness with increasing lifetime exposure to smartphones (odds ratio 2.05, 95% CI1.24–3.38) [305] have been reported.

6.1.3. Visual, accommodative, and oculomotor alterations

In digital eye strain, changes in the ocular surface and tear film can also trigger visual disturbances such as decreased visual acuity, decreased contrast sensitivity, increased glare and increased total optical aberrations [32,382,383]. This is due to the tear film being the external refracting surface for incident light and disruptions in tear film thickness between blinks having the potential to create localized changes in aberrations [339,383,384].

While not directly related to the ocular surface, clinicians must note that adequate accommodation and oculomotor functions are necessary to perform near visual activities and sub-optimal correction can contribute to digital eye strain [16,337,385]. Accommodation and oculomotor alterations can occur because of reduced binocular accommodative facility, asthenopia, uncorrected refractive errors, insufficient convergence and reading at a short distance [16,22,29,338,339,346]. Binocular accommodative facility was significantly reduced in young adults after 60 min of reading from a digital device and ocular symptoms of tiredness, sleepiness, and discomfort were increased; however, no non-digital task was compared [346]. A study found a significant reduction in vergence after 8 h of computer working [386], while another study did not find changes in the near point of convergence after 4 h of computer work [387]. Pupil size varies when performing near tasks, but alterations in pupil size were not associated with the onset of digital eye strain symptoms [16].

Alterations in accommodation can be associated with symptoms of blurred vision, asthenopia, reported focusing difficulties, tiredness, fatigue, weakness of the eyes and headache, each having a prevalence of around 50% in a cohort of computer users [16,22,29,338]. The number of hours per day of digital device use is strongly associated with the development or worsening of these symptoms [29,299]. A survey of adolescents found that those using digital devices 4 h/day or more had significantly more convergence insufficiency symptoms, near exophoria, negative fusional vergence, negative relative accommodation and reduced accommodation amplitude than those using digital devices for less than 4 h daily, with symptoms increasing during the duration of an on-line class [299]. While most studies focus on young adults, digital eye strain can also occur in individuals with presbyopia due to factors such as sub-optimal visual clarity.

6.2. Vision

Visual disturbance with digital eye strain can be associated with a poor quality tear film and ocular surface, as well accommodative and oculomotor alterations. Visual performance and comfort have been mostly evaluated in the past using subjective symptom questionnaires, with “blurred vision” “while viewing the text” and/or “at distance at the end of the near task” forming a common complaint, among others (e.g. diplopia and photophobia) [14,17,31,62,338,365,388–390].

6.2.1. Visual acuity and contrast sensitivity

Visual acuity is the most frequently used measure to assess the integrity of visual function because it forms a simple and easy method of assessing visual capability, referring to the smallest high-contrast static optotype (expressed as the visual angle of resolution) that can be detected or recognized by the patient [391,392]. Conventional visual acuity testing has not been sensitive enough to detect patients with digital eye strain symptoms [21,390,393]. However, prolonged viewing of digital electronic devices with reduced screen sizes requires higher visual demands (and a better visual acuity), compared to that required for printed material, since texts are composed of small and low contrast letters [210,338]. In addition, closer working distances are usually adopted while viewing material on smartphones [204,210], which may pose a need for a different refractive correction, especially in presbyopic populations [390]. Thus, spectacles lenses which optimize vision for the display distance (referred to as occupational lenses), often seem to reduce digital eye strain symptoms (see Section 8.5) [394–397], but progressive lenses for computers are not advantageous over other forms of refractive correction [398].

The contrast of the retinal image, even in a healthy eye, is attenuated due to ocular media imperfections, giving rise to higher order aberrations and scatter [399–401]. Thus, subtle differences in the contrast of any object or pattern might affect its visibility [402]. There are no studies exploring the association between digital eye strain symptoms and contrast sensitivity. Conversely, contrast sensitivity has been found to be reduced in patients with dry eye [403–406].

6.2.2. Reading performance

In modern society, the ability to read is a primary objective of functional vision, with sentence-level reading acuity tests, such as the Colenbrander, MNRead [407] and Radner cards [408], being the simplest to use [409,410]. The International Reading Speed Texts is a more demanding test with longer standardized passages to provide an accurate estimation of reading speed, but short enough to help prevent fatigue effects [411–413]; it was designed to assess the impact of visual

factors and ocular disease, such as age-related macular degeneration and glaucoma, on reading [414,415]. Studies have also measured eye movements simultaneously during reading, as a surrogate indicator of reading performance or to understand the impact of eye movements on reading [21,388,412,416]. Since reading is the most common task that requires sustained near vision, it is not surprising that reading performance forms a strong predictor of vision-related quality of life [410,417], while reading difficulty is a frequent complaint among individuals experiencing digital eye strain symptoms [416,418]. Reading from digital displays can be facilitated by increasing the refresh rate [419], whereas reading speed is hampered in the presence of bright sources causing discomfort glare [420].

6.2.3. Discomfort and disability glare

Glare is defined as an unpleasantly bright light or a luminance range that is too large. Disability glare is caused by the loss of retinal image contrast caused by intraocular light scatter which produces a veiling luminance over the field-of-view. Discomfort glare causes an annoying or painful sensation and is defined as a subjective feeling of annoyance and discomfort caused by a bright light in the field-of-view, without necessarily impairing the visibility of objects. The current standard method for assessing discomfort glare is with subjective rating scales [421]. Objectively discomfort glare has been evaluated by recording the electromyographic responses of the ocular muscles [422,423], which may form a sensitive objective measure for such conditions [389]. The source of glare, when using digital devices, is the light from the digital display or from artificial lighting in the surrounding environment [24,424–426]. Digital device use increases discomfort glare, which affects user performance [14,390,420] and may constitute a major cause of digital eye strain symptoms.

6.3. Oculomotor

Sustained near tasks elicit the near triad, consisting of diminished accommodative and vergence functions, and changes in pupillary response and dynamics [16,386,387,393,427–432]. These occur with both digital screen use and paper-based work, with no convincing evidence for differences [16,365,387,393,427,433–436]. These oculomotor effects have been proposed as indicators or indeed drivers of asthenopic complaints in digital device users, but evidence remains scarce [16,21,334,427,436–438]. The smaller font sizes of smartphones compared to larger screens or print media typically involve even shorter viewing distances and asymmetric head postures; emerging evidence suggests that the smaller font sizes are associated with more pronounced accommodative lag [162,210,439], potentially leading to greater symptoms [204], but definitive, long-term effects remain unstudied [346,440]. These effects appear to be transient, returning to baseline values shortly after ceasing digital display use. While evidence of chronic effects is not available, developing sustained symptoms in the context of ubiquitous digital device use appears plausible [16,21]. Studies in this area often involve small cohorts, with young, healthy participants, with much shorter screen exposure durations than might be experienced during current heavy usage patterns of digital devices.

6.4. Critical flicker fusion frequency

Critical flicker fusion frequency is defined as the lowest level of continuous flicker that is perceived as a steady source of light and has been shown to vary with a number of stimulus factors, including intensity, size, color, contrast, retinal eccentricity, and task duration, as well as the participant's age and level of light adaption [441–443]. A reduction in critical flicker fusion frequency has been interpreted as a proxy measure of eye fatigue, attributable to a decrease in alertness [16,109,116]. However, the validity of this measure is debated, as some studies have been able to detect negative changes in critical flicker fusion frequency with digital eye strain-related subjective ocular complaints [444,445], whereas others have not [332,446–449]. It is further unclear whether critical flicker fusion frequency is different following sustained digital display use relative to that after reading paper, or between different screen technologies [109,332,445,446]. The relatively low refresh rates of early cathode ray tube screen technology may have prompted a focus on critical flicker fusion frequency as a measure for visual fatigue. However, in the context of much higher refresh rates of modern screen technologies (see Section 2.2.3) its utility as an objective measure of digital eyestrain symptoms remains unclear [21,264,332,419,450].

6.5. Refractive development (myopia)

Near cognitive tasks can induce a small, transient and reversible myopic shift, known as 'near work induced transient myopia', that does not significantly affect visual acuity but has been occasionally associated with asthenopic complaints [21,387,393,432,451,452]. Extended computer use has long been considered a risk factor for myopia [452–457], although not in all studies [458,459], with education, near work and reduced outdoor time being recognized risk factors for myopic onset and progression from an early age [205,453,456,460–463]. However, there is no compelling evidence of a significant increase in the risk of myopia onset or progression with digital device use compared to other forms of near work in adults. In children, several recent large-scale studies, systematic reviews, and meta-analyses have reported mixed findings, with digital device use being either not or only moderately associated with myopia [464–466].

A large cohort study of 5,074 children found that computer use at age 9 years was weakly associated with myopia development (odds ratio = 1.005 [95% CI 1.001–1.009]); reading time had a stronger association with myopia, possibly because of a shorter near work distance [464].

A systematic review of 15 studies involving a total of 49,789 children aged 3–19 years found mixed results for an association between the hours children spent using digital screens and myopia, with half of the studies failing to confirm an association. Interestingly, the more recent studies in this review seemed to show a trend of an association between myopia and increased screen time [465]. An increased myopic risk was also reported in the context of the COVID-19 pandemic, attributed to significant increases in screen time [467].

Emerging evidence suggests that smartphone and hand-held device use may be more strongly associated with myopic risk [468]. Handheld devices have smaller screen sizes and are used at shorter working distances, for longer periods of time, compared to laptops and computers. This places higher demands on accommodation and further reduces time spent outdoors, two important risk factors for myopia. Interacting defocus signals associated with accommodative instability may also play a role in myopia development [466]. A meta-analysis of 27 studies on 25,025 children aged 6–18 years found that each additional hour per week of near-vision work increased the odds of myopia by 2% [205], although there was some evidence of publication bias favoring this association and the quality of included studies was not assessed. Another well-conducted systematic review of 33 studies and meta-analysis of 11 studies also indicated that smart device use by children (3–16 years old) may be associated with myopia progression [466].

Several limitations in these studies warrant a cautious interpretation of results, including the use of self-reported measurements of screen time and non-validated questionnaires, relatively small numbers of studies included in meta-analyses and over-representation of Asian populations with high myopia prevalence. Singling out digital screen time as a causative factor remains difficult, given that myopia prevalence, especially in some East Asian countries, increased several decades before digital devices were introduced [466] and digital screens have replaced pen and paper learning, making a direct comparison difficult.

7. Impact

The emergence of new technological developments, hi-tech computational enhancements, and faster internet assists the workforce with management of high volumes of information to allow increased productivity. However, the presence of digital eye strain has been associated with lower quality of life [319] and reduced work productivity [469].

7.1. Productivity

Other than causing personal discomfort to the individual themselves, digital eye strain may have a significant economic impact. Symptoms may slow down completion of the digital task, increase the number of errors made, or require the affected individual to take more frequent breaks.

7.1.1. Ocular symptoms

Ocular symptoms associated with digital eye strain consist of general sensations of discomfort of the eyes, including pain/irritation in and around the eyes, eye strain, soreness, tired eyes, headaches and dryness symptoms [230,334]. Recurrent blurring and transient loss of vision due to extended use of computers or smartphones is not uncommon [22,470] and have a detrimental effect on productivity. A small study [471] reported that productivity improved with increased ocular comfort following regular microbreaks (three 30 s and one 3 min 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 [471]. Productivity loss due to dryness symptoms in Japanese office workers in 2014 was valued at $6,160 (United States) per person annually [345], while the total annual loss due to dry eye disease in the United States of America over a decade ago, was estimated to be $55 billion (United States dollars) [472]. Since visual and digital display use have been implicated as a contributing factor to dryness symptoms and potentially some dry eye disease, it is therefore likely that digital eye strain, as with eye dryness symptoms [473,474], significantly reduces work productivity and negatively affects quality of life.

7.1.2. Visual symptoms

Blurred vision is one of the most common visual symptoms experienced by visual display users, and it has been estimated that wearing a computer-specific refractive correction could increase productivity by 2.5% or more [469]. A double-masked, placebo-controlled, randomized study in 19–30 year-olds estimated that productivity, based on time to completion of a computer task, varied up to 28.7% with 2 D cylinder miscorrection [469]. However, these occupational lenses, designed particularly for presbyopes, are viewing distance-specific, and may be inappropriate for performing tasks at viewing distances different from that of a desktop computer. Improved efficiency has been reported following the introduction of high-resolution monitor displays (see Section 2.2.2) and wear of an optimal visual correction for the relevant working distance (see Section 8.5).

7.1.3. Musculoskeletal symptoms

Digital eye strain associated with near work experienced during or related to computer use may induce a visually stressful situation resulting in changes to body posture [475,476]. Musculoskeletal disorders of the neck and upper limbs can impact the shoulders, upper arms, elbows, forearms, wrists, and hands [477]. Productivity can be negatively affected by musculoskeletal symptoms in computer users [478]. Musculoskeletal injuries associated with computer use may account for at least half of all reported work-related injuries [325,479–481] and were reported to be the second highest reason for sickness certification in the United Kingdom in 2005 [482]. Modelling estimates that the prevalence of neck, shoulder and arm symptoms in computer workers could be as high as 62% [483]. It is therefore not surprising that the cost of work-related musculoskeletal disorders is high (Table 3), and the effects of the COVID-19 pandemic were found to be a contributory factor to increased work-related musculoskeletal injuries [484].

7.2. Quality of life

It is known that digital engagement can positively influence quality of life for older people [489]. However, few studies have investigated whether digital eye strain influences a digital device user's quality of life. In addition, due to strong inter-variable correlations within structural models, it is difficult to establish the exact consequence of digital eye strain on quality of life. One study of 638 university employees demonstrated that digital eye strain had a small, but significant, impact on quality of life after controlling for job quality [319]. The correlation was substantially greater between ocular and physical symptoms whereby blurry vision, dryness and eye strain were all highly correlated with back, arm and leg pain. More is known about the effect of dry eye disease on quality of life. Increased severity of dry eye disease has a significantly adverse impact on physical health [490–492] and mental health [492,493]. A negative impact on sleep and mood have also been reported, with sleep disturbance being significantly associated with dry eye disease in men and women [133], and is significantly higher in dry eye disease patients compared to those with other ocular conditions such as glaucoma or retinal disease [494] (see the *TFOS Lifestyle: Impact of lifestyle challenges on the ocular surface* report) [495]. Use of computers, smartphone, game console and TV in the hour before going to sleep, and >4 h total daytime screen use after school have all been associated with increased sleep deficiency [496]. A decrease in functional visual acuity has also been shown to negatively affect quality of life in patients with dry eye disease [382,497].

7.3. Impact of the COVID-19 pandemic

Digital device use was exacerbated during the pandemic due to the closure of schools, when educational provision became reliant on digital device-assisted online classes [299]. Several studies have evaluated the impact of these changes during the pandemic and reported a high prevalence of digital eye strain, dryness symptoms and asthenopia, associated with increased use of digital devices (increased daily and total screen time) [285,299–301,316,320,344,346,348,349], in children, adolescents [299,300,346], and university students participating in online schooling [285,301], in digital display users [344] and the general population [301,316,320]. The mean hours of digital device use reported in studies during the pandemic ranged from 2 to 9 h daily [285,299,300,316,320,346,349], with the prevalence of digital eye strain ranging from 12 to 95%, increasing with longer duration of digital device use [285,299–301,316,320].

A cross-sectional survey study found an increase in screen time during the pandemic compared to before the pandemic (57.0% vs 10.9% had ≥6 h a day of digital device use). The main risk factors for digital eye strain were found to be longer screen time (with reduced screen time stated as a protective odds ratio 0.636, 95% CI = 0.47–0.85 for not

Table 3
Overview of cost-related musculoskeletal injuries. Adapted from Hoe et al., 2018 [480].

Author (year)	Location	Costs
Mathers 1999 [485]	Australia	17% of the total health system costs
Buckle 1999 [486]	European Union	Up to 2% of Gross Domestic Product
HSE 2020 [484, 487]	United Kingdom	£7 billion annually
USBJI 2015 [488]	United States of America	5.73% of Gross Domestic Product

having digital eye strain), refractive error and having the screen closer than 20 cm away, as well as using devices in the dark and taking little to no breaks [301]. Another study on digital display workers found a significant increase in all digital eye strain symptoms accompanying an increase in screen time from 7.4 to 9.5 h/day from before to during the pandemic [344]. A survey on children (mean age 13 years) undertaking online schooling found a significant increase in the hours of digital device use from 1.9 to 3.9 h a day during the pandemic. Of this cohort, 50% were identified as having digital eye strain (11% reported as 'severe'), with independent risk factors for digital eye strain being age >14 years, male sex, smartphone use, >5 h of digital device use and use of mobile games >1 h a day [299]. A study involving school children (mean age 12 years old) found 97% reported at least 1 symptom of digital eye strain or dryness symptoms, with the most prevalent symptoms noted to be heaviness of the eyelids (80%) and eye redness (69%) [300].

8. Interventions

There is a large demand for treatments to relieve symptoms of digital eye strain. While interventions focused on modifying digital device behaviors in families have shown some success in cultures such as China [498], in most cases it is difficult to encourage reduced digital screen use by individuals. Many therapies are available for managing dry eye disease [499] and given the association between dry eye symptoms and digital eye strain symptoms (Spearman correlation = 0.74) [29], management of ocular surface disease might be expected to assist in reducing digital eye strain symptoms [16,17].

As symptoms of digital eye strain are necessarily subjective, a key consideration in the interpretation of results is the adequacy of participant masking. Studies in which participants are not adequately masked to intervention assignment risk bias toward results favoring the intervention [500]; it is therefore difficult to make an accurate assessment of treatment efficacy when there is potential for ascertainment bias.

8.1. Rest breaks and the 20/20/20 rule

Among published studies, daily digital display duration thresholds associated with symptoms varied from 1 to 2 h/day [501] to 8 h/day [502]. In a review of articles indexed on the PubMed database, only 4 out of 26 studies [503] did not find a positive association between increased daily duration of digital display use and eye dryness symptoms [176,275,504,505]. The 20/20/20 rule is commonly recommended for minimizing dryness symptoms and digital eye strain during digital screen use, proposing that users take a 20-s break every 20 min and focus on an object at least 20 feet away. Though acknowledged by organizations such as the American Academy of Ophthalmology, the American Optometric Association, and Canadian Association of Optometrists [306], there has been limited peer-reviewed studies confirming efficacy of the 20/20/20 rule. An African study reported a beneficial effect on reducing symptoms, but compliance was not monitored so positive findings could have resulted from a placebo effect [506]. A recent study demonstrated a decrease in ocular symptoms, accompanied by an increase in the number of breaks but of shorter duration per day, as a result of 20/20/20 rule reminders [507]; however, 2 weeks was insufficient to considerably improve binocular vision or dry eye signs and improvements were shortlived. It was noted that spontaneous breaks in laptop use were common and that users over-estimated their actual duration of computer use [507].

In relation to studies of rest breaks to reduce digital eye strain, there are two relevant randomized controlled trials [508,509], both by the same lead author, reporting benefits in ocular and musculoskeletal comfort, although ocular surface parameters were not assessed [508,509]. In addition, there are studies demonstrating that regular breaks during digital screen use are associated with fewer ocular dryness-related symptoms [286,295,296,321]. Therefore, whilst there remains biological rationale for the potential benefit of rest breaks for reducing digital eye strain, and these approaches are arguably low risk, have no consumer cost and are promoted by some professional bodies, there remains a need for further robust evaluations to provide greater clarity about their potential clinical merit.

Digital media users commonly report spending too much time on their screens and a strong desire to reduce screen time [510,511]. Various mobile apps and mainstream operating systems incorporate "digital wellbeing" programs aimed at modifying user behavior through monitoring and limiting media use and promoting a more conscious digital 'diet'. The relationship between the duration of screen use, blink behavior and digital eye strain suggests that a reduction in screen time would benefit digital eye strain-associated concerns. However, the use of digital wellbeing interventions in the context of digital eye strain remains unstudied and other wellbeing studies have been deemed methodologically inconsistent, with inconclusive results [510,511]. Current approaches rely largely on self-monitoring techniques which are deemed insufficiently restrictive to promote behavioral change in users. In fact, it is reported that most attempts at reducing or abstaining from screen time seem to fail [510,511].

8.2. Improving blinking

Blink reminders/animations have been applied in five studies with the purpose of increasing blink rate [512–516]. One of the animations covered 20% of the screen for 0.6 s, thereby reminding the user to blink during digital display use [515]. Another study allowed the animation to be customized by the user [516]. In the remaining three studies, the software was made to increase blink rate without interfering with the concentration of the users [513,515,516]. All five studies enhanced the blink rate during digital screen use, however, only three were able to improve the patients' symptoms and only in the short term [512,515,516]. Instructing patients with dry eye disease to perform a 10-s cycle of blinking exercises every 20 min during waking hours for four weeks resulted in improvements in symptoms, an increase in non-invasive tear breakup time and a decrease in the proportion of incomplete blinks. However, one quarter dropped out of the study, there was no change in tear meniscus height or lipid layer thickness, participants reported performing an average of 25.6 daily blinking exercise cycles daily (which is quite onerous), and the duration of the maintained effect was not assessed [517].

8.3. Oculomotor exercises

Oculomotor exercises are used to treat or train various aspects of ocular and visual function. There is limited evidence for the efficacy of ocular exercises in treating convergence insufficiency [427,518]. For all other applications, evidence of the efficacy of eye exercises was deemed insufficient or unconvincing. There is only one study investigating oculomotor exercises in the context of digital eye strain accompanying digital screen use (in the form of virtual reality helmets), which suggested eye exercises are beneficial, but this was tested only with a bespoke questionnaire [519]. In addition, an investigator-masked randomized controlled trial showed that 60 days of eye exercises included as part of daily 1-h yoga practice reduced reported visual discomfort from computer use [520]. Given the role of vergence in digital device use, eye exercises or posture changes may be of use to alleviate convergence insufficiency, especially in digital screen users already suffering from convergence anomalies. However, experimental evidence on oculomotor exercises for reducing digital eye strain is lacking.

8.4. Ergonomics and environmental changes

Office ergonomic training and use of highly adjustable chairs was found to reduce ocular symptoms in office workers [521,522]. Four cross-sectional studies explored the effect of the gaze angle between eyes and screen on dryness symptoms [275,296,321]. Two studies found an

association between the gaze angle and digital eye strain symptoms, concluding that a gaze angle lower than eye level is beneficial, without stating an ideal angle [296]. Contrary to this finding, the risk of dryness symptoms using hand-held digital devices, which are typically placed lower than eye level, was greater compared to desktop digital devices (but not controlling for duration of use) [176]. The other two studies were not able to find any correlation between the angle of gaze and digital eye strain symptoms [275,321]. Three studies assessed the impact of the viewing distance on dry eye symptoms [200,286,321]. Two of the studies concluded that the optimal viewing distance should be either <51 cm [286] or 52–75 cm [200], whereas the third did not find any association between symptoms and viewing distance [321]. Adjusting screen brightness in accordance with the ambient light reduced the prevalence of digital eye strain [286,321], but did not influence the severity of symptoms [321]. One prospective [523] and three cross-sectional [275,286,321] studies found that reducing glare had a beneficial impact on digital eye strain symptoms, leading to advocating for the use of anti-glare screens to reduce digital eye strain allowing a more normal blink rate to be maintained [523].

Increasing light intensity in the workplace reduced the risk of low tear film stability in office workers [524], whereas low air humidity and air-conditioning in an office environment increased the risk of dryness symptoms [524] and increased the severity of digital eye strain [286]. Desktop humidifiers improved patients' symptom scores and tear film stability in office workers [525,526]. Various facial devices, including goggles, spectacles and eye masks, have been applied to treat and prevent dryness symptoms in digital display users [527–530]. Virtual reality headsets were found to be superior to conventional computer use, resulting in an improved tear film stability [251] and lipid layer thickness [531] (see Section 2.3).

8.5. Refractive correction

Digital eye strain symptoms are considerably worsened by an uncorrected or under-corrected refractive error [532–536]. As little as 0.50 to 1.00D of uncorrected astigmatism can significantly increase symptoms [427,536,537]. Therefore, refractive correction is commonly the first line treatment for digital eye strain, with monofocal glasses, as well as various designs for progressive computer glasses being commonly prescribed in clinical practice. A Cochrane systematic review and meta-analysis of 8 studies with a total of 381 participants found that, in the long-term, progressive computer glasses do not considerably reduce digital eye strain-associated complaints compared to other spectacles, regardless of optical design; however, use of 'computer' (intermediate distance focused) glasses alleviated headaches 10% more than single vision distance refractive correction [398]. However, the quality of evidence in all studies was deemed low or very low, leading the authors to claim uncertainty over their conclusion. In addition, correction of presbyopia did not reduce reported digital eye strain [538]. Contact lenses or refractive surgery remain unstudied in this context.

8.6. Blue-blocking interventions

Relatively short-wavelength blue light (380 nm–500 nm), carries a higher energy per photon than longer wavelength visible light. Animal [539,540] and cell culture [541,542] studies show potential for retinal phototoxicity from blue light, although this is dependent on the wavelength, as well as the intensity and duration of exposure. In view of this, international standards exist to define limits for safe blue light exposure, below which ocular damage is unlikely to occur. Whilst sunlight is the primary natural source of blue light in the environment, many modern indoor light sources (for example, light-emitting diodes, liquid crystal displays and fluorescent lamps) have emission spectra that peak at blue light wavelengths. Although increased use of digital technologies that adopt these light sources has heightened concerns about the potentially harmful effects of blue light on eye health, these sources are not considered to represent a biohazard, even from sustained viewing [543] (see Section 2.2.1).

'Blue-blocking' or 'blue light-filtering' ophthalmic devices (e.g. spectacle lenses, contact lenses and intraocular lenses) have dyes or coatings that selectively absorb varying degrees of short-wavelength visible light [116] and were initially developed primarily on the rationale of mitigating the potential risk of retinal toxicity from blue light [544,545]. Blue light has also been hypothesized as a potential cause of digital eye strain [16], although this remains contentious given that the potential mechanism underlying such an effect is unclear [351]. Nevertheless, a diversity of blue-blocking spectacle lenses are now commercially available, some of which have been suggested to reduce eye strain with digital screen use, and are being routinely prescribed by eyecare practitioners for this purpose [546,547]. A recent systematic review [548] identified three relevant randomized controlled trials (Table 4) [351,444,549] with 166 adult participants using interventions from 2 h to one week and concluded that there was low certainty for any benefit with the use of blue-blocking lenses relative to non-blue blocking lenses. Non-randomized studies have examined ocular surface changes with 'blue-blocking' spectacle lenses [550], but even with 50% blue light attenuation [551], no significant effects were found. A randomized controlled trial found no difference between blue-blocking lenses in combination with or without a +0.4 diopter power addition [552]. A contralateral eye pilot study of 'blue-blocking' contact lenses [553] reported improved tear film stability in the eye using the blue light lenses, but the study was not randomized and the clinical significance of the reported effect is unclear. Other considerations relevant to the interpretation of these studies include a lack of consistent digital device exposure and measurement of environmental conditions (for example, humidity and temperature) that may affect ocular surface symptoms and signs.

Ocular exposure to blue light can also be modulated by non-lens interventions, such as screen attachments, internal settings on digital devices and downloadable software. Although rigorous clinical trial evaluations of these interventions are currently lacking, 'blue-blocking' screen filters have been reported to be no more effective at reducing digital eye strain than an equiluminant neutral density filter [554–556]. Effects on the ocular surface were not evaluated in any of these studies. In addition, a systematic review evaluating colored overlays in general found no reliable evidence base that they alleviate reading difficulty or discomfort [557].

Downloadable software to restrict the color palette on digital device displays and 'night' mode options built into some digital devices have also claimed to offer potential benefits in reducing blue light exposure and promoting sleep quality [558]. In general, these act to bias the light spectrum emitted from digital device screens towards longer wavelengths (warmer colors). However, there is limited published research evaluating the efficacy of these forms of blue light control technologies (see Section 2.2.1). A crossover study of 30 adults found reducing blue-light emissions by 20% during a 2-h reading task on a tablet in the late evening reduced subjectively reported dryness-related symptoms compared to performing the task on the unfiltered tablet [559].

8.7. Interventions to improve tear film quality and/or quantity

8.7.1. Artificial tear products and topical formulations

Artificial tear products, which aim to supplement the tear film, are a mainstay of dry eye disease management [499,560]. In general terms, these agents lubricate the ocular surface and enhance tear volume, but are heterogeneous in their formulations and on-eye performance [560]. Although many studies have investigated artificial tear therapy for reducing signs and/or symptoms of dry eye disease, few have formally investigated their efficacy for digital eye strain. The use of ocular lubricant eye drops has been reported to reduce ocular symptoms of dryness, tiredness and focusing difficulties when performing a computer task [561,562]. Three artificial tears designed to act on different tear

Table 4
Key characteristics of randomized controlled trials that have evaluated blue-blocking lenses for digital eye strain.

Study	Trial design	Participant population	Intervention(s)	Comparator	Intervention duration	Outcome
Dabrowiecki et al. (2020) [549]	Single-masked, parallel arm	Radiology residents (n = 20)	Blue light-blocking single-vision lenses, worn from 8:00 a.m. to 5:00 p.m. each day.	Non-blue light-blocking single-vision lenses worn from 8.00am to 5.00pm each day.	1 week	Only difficulty focusing at near reduced
Lin et al. (2017) [444]	Single-masked, parallel arm	Adults not performing visual display terminal work for ≥1 h beforehand (n = 36)	High vs low blue light-blocking single vision lenses.	Non-blue light-blocking single vision-lenses	2 h (single session)	Reduced symptoms and increase in critical flicker fusion frequency
Singh et al. (2021) [351]	Double-masked, parallel arm	Symptomatic computer users (n = 120)	Blue light-blocking single-vision lenses with intervention framed in a positive vs negative light to participants	Non-blue light blocking single-vision lenses with intervention framed in a positive vs negative light to participants	2 h (single session)	No difference in symptoms or critical flicker frequency

constituents (i.e., lipid, aqueous or mucin) on tear film parameters were randomly allocated to 27 individuals with dryness symptoms related to external causes (defined as daily contact lens wear or computer use ≥4 h per day) for 1 month [563], but the lack of any differences between groups is not surprising given the underpowered sample size [377].

8.7.2. Topical mucin secretagogues

Mucins are an integral component of the tears that limit ocular surface dessication [564]. An open-label, active-comparator randomized controlled trial undertaken in Japan compared topical rebamipide and diquafosol in office workers with dryness symptoms who used a computer for >4 h per day. Relative to baseline, participants in both intervention arms showed improved tear film stability at four weeks follow-up and reduced dryness symptoms at 8 weeks of follow-up. There were no local or systemic side effects noted, and both secretagogues showed similar efficacy [565]. In a non-randomized intervention study in patients with dryness symptoms, topical diquafosol, dosed 6 times per day, was found to be effective in reducing some ocular symptoms, corneal fluorescein staining and enhancing tear breakup time, relative to an artificial tear control [566].

8.7.3. Other eye-focused interventions

A recent single-masked randomized controlled trial evaluated the effect of an eyelid warming device applied once, or over 2 weeks, in 22 digital screen users with poor tear film stability compared to a non-warmed eye-mask in 23 controls [529]. Although improvements relative to baseline in tear breakup time and staining scores in the eyelid warming group were reported even after a single treatment, between-group comparisons were not described. In a prospective, within-participant intervention study, 22 adults with dryness symptoms who regularly undertook computer tasks were evaluated on separate days during which they had either worn warming moisture goggles for 15 min or used sodium hyaluronate 0.1% artificial tear eye drops [527]. Comparing data measured after a single exposure at 60 min post-intervention, dryness symptoms were lower and tear film stability was higher when the moisture goggles were used, but there were no significant inter-condition differences in tear meniscus height or ocular bulbar redness. A randomized control trial of a single treatment with a latent heat device (n = 25), liposomal spray (n = 28) or heated warm compress (n = 28) found all improved non-invasive breakup time and lipid layer grade [567]. Similar promising findings were reported in a single-visit study involving humidity goggles and liposomal eye spray [528].

8.8. Dietary interventions

8.8.1. Omega-3 fatty acid supplements

Oral omega-3 fatty acid supplements, in various formulations, have been extensively investigated as a potential therapy for dry eye disease. These agents are generally considered to modulate systemic inflammatory pathways, and have been shown to reduce tear pro-inflammatory cytokine levels in patients with dry eye disease [568] and promote corneal nerve regeneration in individuals with diabetes [569]. Although individual randomized controlled trials have reported conflicting efficacy, a 2019 Cochrane systematic review concluded that based on the totality of the evidence, there was a possible role for oral long-chain omega-3 supplementation in managing dry eye disease [570]. The effect on digital eye strain has not been studied. The effects of essential fatty acids in modulating ocular surface health more broadly is discussed in detail in the *TFOS Lifestyle: Impact of nutrition on the ocular surface* report [571].

Two, parallel-arm randomized controlled trials, published by the same lead author, investigated the use of oral long-chain omega-3 fatty acids in individuals with presentations consistent with digital eye strain [572,573]. Symptoms and tear film stability improved with supplementation in both studies, but not in the control group, whereas other ocular surface metrics were more variable; one study was graded to be at high risk of bias and the other graded as some concerns (see Section 8.11.2.3.3). A recent systematic review [548] that pooled data from these two studies, reported that despite high statistical heterogeneity, there was moderate certainty for reduced dryness symptoms with the omega-3 supplement, relative to placebo, over the 45–90 day intervention periods. The dose of omega-3 fatty acids used in the trials ranged from 600 mg to 2400 mg of combined eicosapentaenoic acid and docosahexaenoic acid per day, which is likely a contributory factor to the observed heterogeneity. Both trials also reported promising outcomes with parallel improvements noted in tear film stability [572,573].

8.8.2. Berry extract supplements

Several randomized controlled trials [303,574–580] have evaluated various forms of berry extract oral supplements, over intervention periods up to 12 weeks, for reducing visual fatigue and dryness symptoms in computer users. The investigated interventions comprise different formulations and dosing regimens of bilberry extract [303,576–580], bog bilberry [577] and macqui berry [578]. The potential mechanism by which these agents might exert their effect as a treatment for digital eye strain is not currently established. Based on pooled data from seven such studies, it has been reported that relative to placebo, oral berry supplementation can improve visual fatigue with small to moderate effects; however, the certainty of this finding was judged to be low, due to incomplete outcome data, selective reporting biases and most studies having commercial sponsorship [548]. There was also low certainty evidence with regard to the absence of safety concerns. Only two trials evaluated ocular surface outcomes [303,578], reporting a higher Schirmer test score after four weeks of oral macqui berry intake relative to a placebo supplement, but there was no effect on tear film stability [578], as was the case with oral bilberry extract supplement [303].

8.8.3. Other supplements

Two randomized, placebo-controlled trials have reported that oral carotenoid supplements can reduce ocular symptoms associated with extended screen time, but neither evaluated ocular surface outcomes

[581,582] Randomized controlled trials have also evaluated a range of 'combination' supplements for treating digital eye strain, including fish oil with bilberry extract and lutein [583], water chestnut extract and lutein [584], lutein, zeaxanthin and blackcurrant extract [585], anthocyanin, astaxanthin, and lutein [586], and lutein ester, zeaxanthin, and extracts of blackcurrant, chrysanthemum, and goji berry (at three doses) [587]. Of these studies, only two evaluated ocular surface parameters, showing no benefit with a lutein, zeaxanthin and blackcurrant extract supplement, relative to placebo, for tear film stability measures over six weeks [586], while another lutein-based supplement showed enhanced tear secretion, measured using the Schirmer test, relative to placebo after 90 days [587].

8.9. Yoga

Yoga, an ancient practice that involves a group of physical, mental and spiritual practices that focus on postures, regulated breathing and meditation [588], has also received interest as a potential strategy for treating digital eye strain. Although the mechanism by which this occurs is uncertain, the leading hypothesis is changes to blink frequency from a heightened state of relaxation [520] or optimized posture. Two published papers [520,589] by the same lead author, describe results from a parallel-arm randomized controlled trial in India that evaluated the effect of yoga relative to a control condition on vision-related outcomes in computer users. Ocular surface parameters were not evaluated. Relative to controls, the yoga intervention group were reported to have less overall self-reported visual fatigue after 60 days [520], but there was high participant attrition (>60%) in both intervention groups, and participants were not masked.

8.10. Traditional medicines

Various traditional medicines have also undergone investigation as potential management options for digital eye strain. Traditional remedies represent a heterogeneous range of approaches, including Triphala eye drops and Saptamrita Lauha tablets [590], Itone herbal eye drops [591,592], Shatavaryaadi Churna and Ghrita and Madhu Anupana orally, Tarpana Karma with Go-Ghrita [593], Tila Taila Padabhyanga (foot massage with sesame oil) [594] and oral triphala ghrita [595]. Although many of these trials report positive results on digital eye strain symptoms with the use of the traditional medicine, most of the randomized controlled trials did not have adequately reported masking methods and were not prospectively registered, which creates a level of uncertainty about the study findings.

8.11. Systematic review and meta-analysis

To date there has not been a systematic review focusing on the effect of treatments for digital eye strain focused specifically on the ocular surface. Hence, investigating the clinical evidence using systematic review methodology to address the question: *Which ocular surface disease management approaches reduce symptoms associated with digital device use?* was deemed valuable to provide insight into whether interventions that target ocular surface disease as a cause of digital eye strain lead to significant improvements in patient symptoms. Unlike the narrative review (sections 8.1–8.10) this systematic review targeted only the highest level of management evidence available from primary research studies, in the form of randomized controlled trials. Due to corresponding heterogeneity, the digital eye strain and dry eye symptom outcomes had to be merged, therefore the findings reflect eye dryness symptoms during digital device use.

8.11.1. Methods

In accordance with the process followed in each of the TFOS Lifestyle Workshop reports [1], the systematic review protocol was prospectively registered on PROSPERO (CRD42022296735). The online systematic review management software Covidence (Veritas Health Innovation, Melbourne, Australia) was used to manage this review.

8.11.1.1. Systematic literature searches. Pubmed and EMBASE were searched using a pre-determined search strategy (Supplementary Materials; Appendix A1) targeting English language randomized controlled trials that investigated any ocular surface disease intervention to reduce symptoms of digital eye strain. Searches were conducted on December 21, 2021 and on November 10, 2022. No date restriction was applied.

Digital eye strain was defined as "the development or exacerbation of recurrent eye signs and/or symptoms related specifically to digital device viewing". Therefore, studies that specifically targeted populations with diagnosed digital eye strain or that investigated the effect of an intervention on symptoms during a specific digital device task were eligible for inclusion.

8.11.1.2. Title and abstract screening. Title and abstracts were assessed independently by two of three authors (GL, RS, JSW) using pre-defined eligibility criteria (Table 5). Eligibility disagreements were resolved through group discussion. When it was unclear whether a citation met the eligibility criteria, the record progressed to full-text screening.

8.11.1.3. Full text screening. Full-text screening was conducted by a single author (GL) according to the eligibility criteria (Table 5). A second author (RS) reviewed all excluded articles to confirm they did not meet eligibility criteria. In ambiguous cases (raised either during first or second review), decisions were made through group discussion.

8.11.1.4. Data extraction. Eligible articles underwent independent data extraction by two review authors (GL, EKA) using a template that was developed based on outcome measures stated in the protocol.

The primary outcomes for this review were the subjective report of digital eye strain symptoms or dry eye symptoms using a composite, summary, or total score, such as the CVS-Q, or Ocular Surface Disease Index. While this review aimed to investigate treatment for digital eye strain specifically, it was anticipated that outcome data on dry eye symptoms during digital device use, a correlate of digital eye strain symptoms [29], might be more commonly reported.

Secondary outcomes included eye strain, fatigue or tiredness (these terms were often ill-defined and used interchangeably), burning,

Table 5
Inclusion and exclusion criteria applied to both the title and abstract screening and full-text screening stages for the systematic review.

Inclusion criteria	Exclusion criteria
1. Study must be a randomized controlled trial (head-to-head studies and cross-over studies were acceptable) 2. Inclusion of an outcome measure relating to symptoms of digital eye strain or symptoms of dry eye 3. Patient population must be participants of any age with digital eye strain or who report target outcomes (see inclusion criterion 2) during a digital device task 4. An intervention aimed at treating ocular surface disease, and falling into one of the following categories: • Behavioral interventions • Environmental interventions • Topical lubricants • Topical pharmaceutical eye drops • Oral pharmaceutical agents • Oral vitamin and/or nutritional supplements • Blue light-blocking lenses • Ophthalmic procedural interventions • Alternative or traditional therapies	1. Not published in English language 2. Non-human studies 3. Not a full-length published journal article (e.g., a conference poster or abstract)

itching, dryness, foreign body sensation or grittiness, watering or tearing, redness, blurred vision, and glare.

To ensure that extracted data could be adequately described using mean and standard deviation statistics (i.e., were not heavily skewed), limitations were placed on the type of data eligible for extraction (Fig. 5). Where median and interquartile ranges were reported, mean and standard deviations were estimated using methods proposed previously [596]. No restrictions were placed on the type of symptom assessment tool employed as this was expected to vary across studies. Disagreements in data extraction were resolved through discussion between the two data extractors (GL, EKA).

8.11.1.5. Quality assessment and certainty of evidence. The Cochrane Risk of Bias 2 tool [597] was used for quality appraisal. As all digital eye strain symptoms were frequently assessed using the same assessment method, digital eye strain symptoms were considered a single outcome for the appraisal. The standard Risk of Bias parallel-group or cross-over trial tool was used as appropriate. Risk of Bias assessments were completed independently by two assessors (GL and SS) and discrepancies resolved through discussion. Where a competing interest was present (for example, where listed as an author), the remaining assessor appraised the article alone. Certainty of evidence was evaluated for all outcomes for which data from multiple studies could be extracted for a given intervention and was completed independently by two assessors (GL, SS) using the Grading of Recommendations, Assessment, Development and Evaluations (GRADE) method [598]. Discrepancies in the GRADE assessments were resolved through discussion between the two assessors.

8.11.1.6. Statistical analysis. When studies had more than one intervention arm (for example, different doses of the same treatment) or more than one comparator arm (for example, same comparator under different lighting conditions), data from both groups were combined using formulae outlined in the Cochrane Handbook [599]. Only data comparing an intervention to no treatment or a placebo were used in the meta-analysis. As symptoms scores were recorded on different scales, standardized mean differences were calculated, to place outcome scores on the same scale (units in standard deviations) and to allow data from different questionnaires to be compared. Both post-baseline and change from baseline data were combined in a single meta-analysis, as the results of such combinations have been empirically shown to produce valid pooled estimates [600].

Statistical heterogeneity was assessed using the I^2 statistic. As heterogeneity was expected in study results, random-effects models were chosen *a priori*. Where considerable heterogeneity was present, defined as $I^2 \geq 75\%$, pooled estimates were not calculated as variation between study findings can make such combining of results invalid [599].

Results are presented as mean ± standard deviation, with 95% confidence intervals (CIs). The R package (R Foundation for Statistical Computing, Vienna, Austria) "meta" was used for meta-analysis. Results were pooled using the inverse-variance method. To proceed with a meta-analysis, two or more studies from the same intervention type had to present data on the same outcome. Funnel plots were used to assess publication bias.

8.11.1.7. Deviations from the protocol. There was one deviation from the published protocol; it was planned that two authors would independently conduct full-text screening of all articles. Due to time constraints, a single author completed full-text screening. Potential bias introduced through this process was minimized by having a second author review all excluded full-texts to ensure they were not inappropriately excluded. Additionally, included full-texts were viewed by other reviewers during data extraction and risk of bias assessments, and any concerns about meeting inclusion criteria raised during this process.

8.11.2. Results

8.11.2.1. Systematic literature review. Fig. 6 provides an overview of the results of the systematic review process, including results of an updated search conducted on the November 10, 2022. Briefly, searches yielded 3,821 results, of which 351 were duplicates. Of the 3,470 unique titles screened, 3,323 (95.8%) titles and 59 (1.7%) abstracts unanimously failed and passed screening, respectively. There were 88 (2.5%) records with conflicting decisions, of which 47 (53%) were excluded and 41 (47%) continued to full-text screening. Cohen's Kappa for inter-rater agreement for inter-rater comparisons was 0.58 (GL vs RS) and 0.53 (GL vs JSW). One hundred articles underwent full text screening and 65 (65%) were excluded (Appendix A2). Thirty-five articles were ultimately deemed eligible for inclusion and underwent data extraction [84,303,351,444,515,516,525,526,529,530,549,555,572–579,583,586,587,590,591,593,595,601–608].

Table 6 summarizes the characteristics of included studies. For all digital eye strain outcomes, a higher score indicates worse symptoms (more discomfort) and a lower score indicates less severe symptoms. Interventions were grouped into the following categories: antioxidant

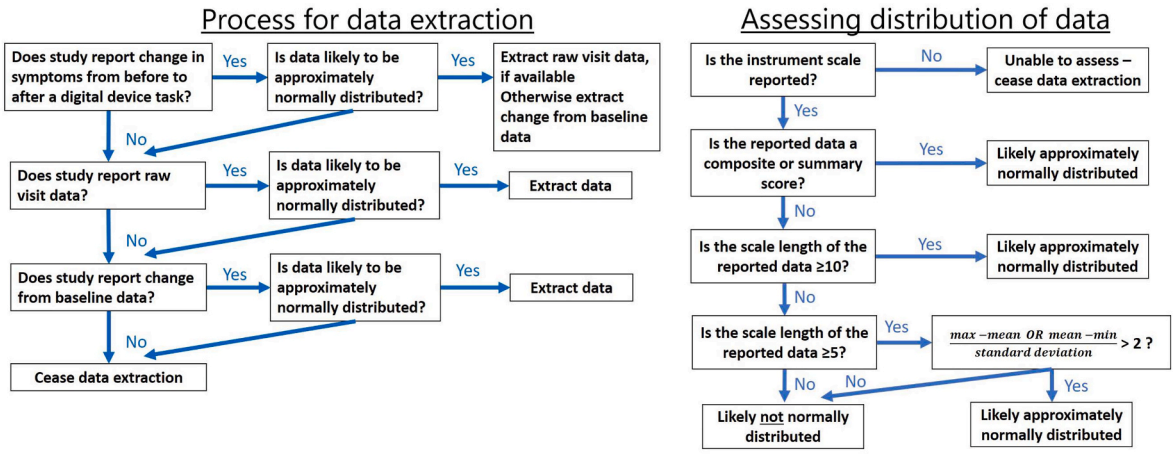

Fig. 5. Flow charts showing (left) the decision-making process regarding which data to extract when authors report more than one type of data for a given study (for example, change and post-baseline score) and (right) process for determining whether outcome data were likely to be normally distributed. Min and max refers to the minimum and maximum possible values, based on the upper and lower limits of the scale used to assess symptoms, rather than the minimum and maximum observed values.

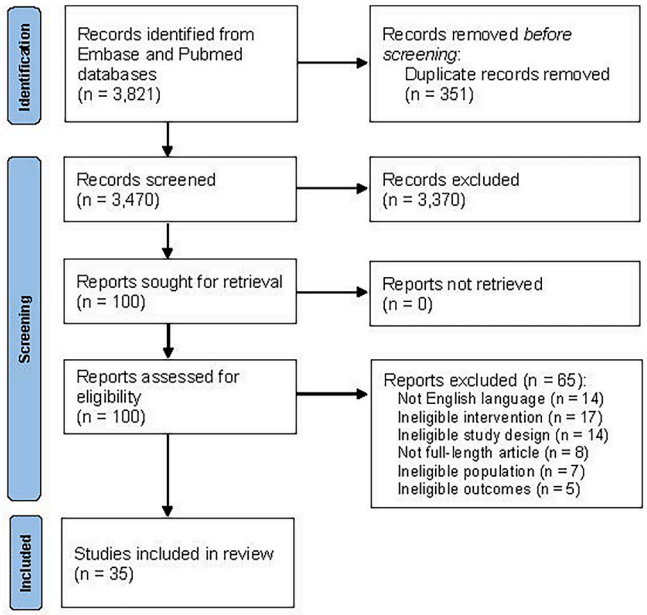

Fig. 6. PRISMA flow chart showing results of systematic literature search and review. Results are reported for the initial search (first result) and an updated search conducted on the November 10, 2022 (second result). Exclusion reasons are described.

supplements, parabiotic supplements, omega-3 supplements, blue light-blocking lenses, topical lubricant eye drops, blink reminders, rest break promotion, display screen, humidifiers, eyelid warming interventions and ayurvedic therapies.

One study assessed digital eye strain in children, another in adolescents and the remaining assessed digital eye strain in adult participants. A mixture of males and females were included in all studies. Of the 28 studies that reported male and female participation, females comprised 38%–90% of the total study sample (median 60%).

8.11.2.2. Risk of bias and certainty of evidence. The Cochrane Risk of Bias 2 tool results are shown in Fig. 7. Only one study was judged to have an overall low risk of bias; 18 studies had 'some concerns', and 16 studies were considered at high risk of bias. Eleven of the eighteen (61%) studies with an overall risk of bias evaluation of "some concerns" received this due to a lack of a pre-specified statistical analysis plan or a lack of information about a pre-specified plan. Another common reason for receiving a "some concerns" classification in domain 1 was a lack of information on the randomisation and treatment assignment methods. All studies with a high risk of bias received this grading due to (among others) concerns in the measurement of the outcome (domain 4), usually related to a lack of, or inadequate, masking of participants. The GRADE certainty of evidence was evaluated for each intervention and outcome where data from more than one study was extracted and is shown in Table 7. Certainty was usually downgraded due to risk of bias, as nearly every included study had either some concerns or was at high risk of overall bias. Some evaluations were additionally downgraded due to inconsistency in the effect estimate or imprecision (either due to small sample size or wide confidence intervals).

8.11.2.3. Primary outcome. Of the 35 articles eligible for inclusion in this study, outcome data were able to be extracted for 22 (62.9%) [84,303,351,444,515,516,525,529,549,572–574,576–579,586,587,602,603,608]. Outcome data on digital eye strain, specifically, were available for five studies, [84,549,577,606,608]. As there was little digital eye strain-specific data, and dry eye symptoms in device users are correlated with digital eye strain symptoms [16], digital eye strain and dry eye symptom summary scores were merged into a single primary outcome variable. Digital eye strain symptoms scores were used in preference to dry eye symptoms scores where data on both outcomes were available from a single study. Primary outcome data were then available for 11 (31.4%) studies [84,335,351,515,516,529,549,572,577,578,587,602,603,608].

The meta-analysis results for the primary outcome, broken down by intervention type, are shown in Fig. 8. On pooled analysis of two studies [351,549], the standardized mean differences effect estimate for blue light-blocking lenses was consistent with no effect and the certainty of evidence was graded as low.

The effect estimates of blink reminder interventions were not pooled due to heterogeneity ($I^2 > 75\%$). Individually, one study [516] classified as having some concerns on risk of bias did not find a significant effect of the intervention on digital eye strain or dry eye symptoms, and the other graded as high risk of bias [515] found that blink reminder software significantly improved dry eye symptoms. The certainty of evidence was graded as very low.

Two studies using an omega-3 fatty acid supplement conducted by the same research group reported improvement in digital eye strain symptoms, relative to the control group [572,573]. These results were not pooled due to high heterogeneity between the studies and an assessment of the certainty of evidence was therefore not made, but individually suggest a beneficial effect with the use of oral omega-3 fatty acid supplementation, with intervention groups having a dry eye symptom score that was approximately 1.5 standard deviations lower than the control group. The high heterogeneity may arise from the different doses used; the dose used in one study [572] (1440 mg eicosapentaenoic acid + 960 mg docosahexaenoic acid per day) was twice that used in the other [573] (720 mg eicosapentaenoic acid + 480 mg docosahexaenoic acid per day). One of these studies was judged to be at high risk of bias and the overall certainty of evidence was assessed as low.

Results from oral anti-oxidant supplement studies were also not pooled due to high heterogeneity. Three studies reported findings consistent with no effect of the intervention on digital eye strain or dry eye symptom scores, while one study found that an anti-oxidant supplement improved symptom score by approximately 1.3 standard deviations, compared to the control group. There were again differences in dosing or specific test product; one [587] used a combined macular pigment (lutein, zeaxanthin) and anti-oxidant supplement (berry extract) whereas other included studies used a berry extract [577,578] or a hydrogen-producing milk product [602] alone. The anti-oxidant dose was not always comparable between studies, using doses of berry/botanical extract of 2,800 mg/day [587], 1,000 mg/day [577] and 120 mg/day [578], and another [602] used 4.2 g/day of active hydrogen-producing ingredients. There was no evidence of publication bias in the funnel plots for all intervention types (Fig. S1). The GRADE certainty of the evidence was very low.

To interpret the standardized mean differences shown in Fig. 8, the baseline standard deviations of the three studies reporting baseline CVS-Q results (10.15 [84]; 6.01 [577]; 3.92 [351]: pooled standard deviation = 7.43) were pooled. A -0.75 standard deviation difference in symptoms relates to approximately a 5.6-unit lower questionnaire score (maximum score = 32), relative to the control group, and a -1.5 standard deviation difference in symptoms score relates to approximately an 11.2-unit lower questionnaire score.

8.11.2.3.1. Anti-oxidant supplement interventions. Ten studies investigated the effect of an anti-oxidant containing supplement in alleviating digital eye strain or dry eye symptoms [303,574–579,586,587,602]. Either primary or secondary outcome data were able to be extracted from all anti-oxidant supplement studies and included in the meta-analysis. Four studies investigated a berry extract dose of 120–160 mg/day [574,578,579,586], three studies used a dose of 480–550 mg/day [303,575,576], and the remaining three studies used a berry extract dose of 1000 mg/day [577], a berry/botanical extract dose of 2,800 mg/day [587] or 4.2 g/day of active hydrogen-producing

Table 6
Characteristics of included randomized controlled trials.

First author and year	Study design	Intervention	Comparator	n	Symptom assessment tool	Participant population	Follow-up time
Anti-oxidant supplement interventions							
Liang 2017 [574]	PG	Oral anthocyanin [115.8 mg/day] (bilberry extract [160 mg/day])	Placebo capsule	22	6-point Likert scale	Adult device users with symptoms	6 weeks
Okamoto 2018 [575]	PG	Oral anthocyanin [60 mg/day] (bilberry extract [550 mg/day])	Placebo capsule	39	VAS	Adult (aged 33–68 yrs) device users with symptoms	12 weeks
Kan 2020 [587]	PG	Oral lutein, zeaxanthin and anthocyanin (chrysanthemum, goji berry and blackberry extract [2800 mg/day[a]])	Placebo capsule	360	China Food and Drug Administration Eye Fatigue questionnaire	Adult (mean age 38 yrs) device users with symptoms	90 days
Okamoto 2019 [576]	PG	Oral anthocyanin [60 mg/day] (bilberry extract [550 mg/day])	Placebo capsule	35	VAS	Adult (mean age 38 yrs) device users with symptoms	12 weeks
Sekikawa 2021 [579]	PG	Oral anthocyanin [43.2 mg/day] (bilberry extract [120 mg/day])	Placebo capsule	32	6-point Likert scale	Adult (mean age 37 yrs) device users with symptoms	6 weeks
Kizawa 2021 [586]	PG	Oral anthocyanin [72 mg/day] (bilberry extract [120 mg/day]), astaxanthin and lutein	Placebo capsule	40	6-point Likert scale	Adult (aged 20–59 yrs) device users with symptoms	6 weeks
Yamashita 2019 [578]	PG	Oral anthocyanin [42 mg/day] (macqui berry extract [120 mg/day])	Placebo capsule	74	DEQS and VAS	Adult (mean age 45 yrs) device users with symptoms	4 weeks
Kawashima 2019 [602]	PG	H_2-producing milk [active: 4.2 mg/day]	Placebo milk	54	DEQS and VAS	Adult (aged 20–59 yrs) device users with symptoms	3 weeks
Park 2016 [577]	PG	Oral anthocyanin [1000 mg/day] (bilberry extract [96 mg/day])	Placebo pill	50	Modified VRSQ	Adult (aged 22–64 yrs) device users	4 weeks
Ozawa 2015 [303]	PG	Oral anthocyanin (bilberry extract [480 mg/day])	Placebo capsule	80	VAS	Adult (mean age 31 yrs) device users with symptoms	8 weeks
Parabiotic supplement interventions							
Morita 2018 [603]	PG	Heat-killed Lactobacillus paracasei capsule [50 mg/day]	Placebo capsule	59	DEQS and VAS	Adult (mean age 40 yrs) device users with symptoms	8 weeks
Omega-3 fatty acid supplementation							
Bhargava 2015 [573]	PG	Oral EPA and DHA [2400 mg/day]	Placebo capsule	456	DESS	Adult (mean age 23 yrs) device users with symptoms	3 months
Bhargava 2016 [572]	PG	Oral EPA and DHA [600 mg/day]	Placebo capsule	522	DESS	Adult (mean age 29 yrs) device users with symptoms	45 days
Combined omega-3 fatty acid and anti-oxidant supplementation							
Kawabata 2011 [583]	PG	Oral EPA and DHA [945 mg/day], anthocyanidin [59 mg/day] (bilberry extract [240 mg/day]) and lutein	Placebo capsule	20	Nakamura's Asthenopia Questionnaire	Adult (mean age 25 yrs) device users with symptoms	4 weeks
Blue light-blocking interventions							
Dabrowiecki 2020 [549]	CO	Blue light-blocking spectacle lenses	Blue light-transmitting lenses	10	CVS-Q	Adult radiology trainees	5 days
Singh 2021 [351]	PG	Blue light-blocking lenses	Blue light-transmitting lenses	120	CVS-Q and VAS	Adult (aged 21–30 yrs) device users with symptoms	2 h
Lin 2017 [444]	PG	High blue light-blocking lenses	Low blue light-blocking or blue light-transmitting lenses	36	Likert-scale questionnaire (5-point)	Adult (mean age 24 yrs) university students without symptoms	2 h
Vera 2022 [555]	PG	Blue light blocking screen filter	No blue light blocking filter	23	5-point ordinal scale	Adults (mean age 22.9 yrs) without symptoms	30 min
Topical lubricant eye drops							
Rajendraprasad 2021 [604]	HH	Carboxymethyl cellulose 0.5% eye drop [DNS]	Hydroxypropyl methylcellulose 0.3% eye drops	180	OSDI	Adult device users with symptoms	90 days
Skilling 2005 [605]	HH	Polysorbate 80 0.5% eye drop [2–4 drops/day]	Tetrahydrozoline hydrochloride eye drop	50	4-point ordinal scale	Adult device users with symptoms	5 days
Blink reminder interventions							
Ashwini 2021 [516]	PG	Blink-blink software	Placebo blink-blink software	46	OSDI	Adult (aged 18–45 yrs) device users with symptoms	4 weeks
Nosch 2015 [515]	CO	Blink-blink software	Placebo blink-blink software	24	OSDI	Adult (mean age 39 yrs) device users with symptoms	7 days

(*continued on next page*)

Table 6 (*continued*)

First author and year	Study design	Intervention	Comparator	n	Symptom assessment tool	Participant population	Follow-up time
Rest break promotion interventions							
Lertwisuttipaiboon 2017 [607]	PG	Educational eye care program promoting rest breaks	No intervention	70	Eye strain (yes/no)	Adult office workers who use digital devices	8 weeks
Zheng 2021 [606]	PG	Live-streaming app to promote rest breaks and physical activity	Standard health education	954	CVS-Q	School children (mean age 13 yrs) using devices for online learning	2 weeks
Display type interventions							
Yuan 2021 [84]	PG	Electronic paper (non-light-emitting) display	Organic light-emitting diode (OLED) display	119	CVS-Q and OSDI	Adult university students (aged 19–30 yrs) without symptoms	2 h
Mou 2022 [608]	PG	Circularly polarized light-emitting display	Linearly polarized light-emitting display	120	CVSS17 and OSDI	Adult university students (mean age 25.9 yrs)	2 h
Humidifiers							
Yee 2007 [530]	CO	Microenvironment glasses	Lubricant eye drop or no treatment	40	OSDI	Adult (aged 20–60 yrs) device users without symptoms	30 min
Wang 2017 [526]	CO	Desktop USB humidifier	Inactive USB humidifier	44	3-point scale: comfort greater, equal, or lesser	Adult (mean age 21 yrs) device users	1 h
Hirayama 2013 [525]	PG	Moist cool air device	No treatment	20	VAS	Adult (aged 23–42 yrs) device users	5 days
Eyelid warming interventions							
Sun 2020 [529]	PG	Eyelid warming steamer	Placebo device (no heat)	45	DEQS	Adult (mean age 36 yrs) device users with symptoms	2 weeks
Ayurvedic therapy interventions							
Sawant 2013 [595]	PG	Triphala Ghrita Tarpan (topical ghee) [DNS]	Eye exercises	60	3-point scale of symptom relief	Adult device users with symptoms	3 months
Gangamma 2010 [590]	PG	Triphala eye drops [4 drops/day] ± oral Saptamrita Lauha [1000 mg/day]	Placebo tablets and eye drops	151	Unclear	Adult device users with symptoms	30 days
Chatterjee 2005 [601]	PG	Herbal eye drop (itone) [4 drops/day]	Lubricant or placebo eye drop	120	Unclear	Adult (mean age 27 yrs) device users with symptoms	6 weeks
Biswas 2003 [591]	PG	Herbal eye drop (itone) [8 drops/day]	Lubricant or placebo eye drop	120	Unclear	Adult device users with symptoms	6 weeks
Dhiman 2012 [593]	PG	Oral Shatavaryaadi Churna [6 g/day] ± topical ghee [DNS]	Counselling on changes in device use behaviors	30	Unclear	Adult device users with symptoms	1 month

Dose and/or frequency of treatment are shown in square brackets. DNS: Dose not specified; PG: Parallel group design; CO: Cross-over design; HH: Head-to-head design; EPA: eicosapentaenoic acid; DHA: docosahexaenoic acid; CVS-Q: Computer Vision Syndrome Questionnaire; CVSS17: Computer Vision Syndrome Scale 17; OSDI: Ocular Surface Disease Index; VAS: Visual Analogue Scale; DEQS: Dry Eye-related Quality of Life Score; MDEQ: McMonnies Dry Eye Questionnaire; DESS: Dry Eye Scoring System; USB: Universal Serial Bus; yrs: years.

[a] Average of the three doses of 1750, 2569 and 4081 mg/day.

ingredients [602]. One study additionally investigated a combination omega-3 and anti-oxidant supplement [583], but its data failed to meet the criteria for being approximately normally distributed and were not included in the meta-analysis (see Section 8.11.2.6). The results of the meta-analysis of secondary outcomes in studies using an anti-oxidant supplement intervention are shown in Fig. 9.

Use of anti-oxidant supplements was not associated with a significant improvement in most secondary outcome symptoms, including ocular burning sensation (standardized mean differences = −0.47 [favors intervention], 95% CI: −1.03, 0.09), with the exception of foreign body sensation, for which treatment was associated with a modest improvement in symptoms. Placebo capsules performed better than anti-oxidant supplements for treating itching. There was no evidence of systematic publication bias in the funnel plots (Fig. S2). For all secondary outcomes, the certainty of evidence was assessed as very low for foreign body sensation, itching, glare and as low for eye strain or fatigue, dryness, watering or tearing, eye redness and blurring of vision.

8.11.2.3.2. Parabiotic supplement. One study investigated a parabiotic supplement with purported anti-inflammatory properties as an intervention for adults with digital eye strain [603]. There was no significant difference in Dry Eye Related Quality of Life score between the intervention and placebo groups (week 4: mean difference = 3.3 [favors comparator], 95% CI: −5.9, 12.5; week 8: mean difference = 2.2 [favors comparator], 95% CI: −7.1, 11.5). Additionally, there was no significant difference in change in reported visual blurring (week 4: mean difference = −0.6, 95% CI: −9.1, 7.9; week 8: mean difference = −1.8, 95% CI: −10.1, 6.5), tearing (week 4: mean difference = −1.1, 95% CI: −9.8, 7.6; week 8: mean difference = 5.3, 95% CI: −2.1, 12.7), glare (week 4: mean difference = −1.0, 95% CI: −11.0, 9.0; week 8: mean difference = −1.6, 95% CI: −7.2, 10.4) and redness (week 4: mean difference = 7, 95% CI: −1.2, 15.2; week 8: mean difference = 5, 95% CI: −3.5, 13.5) from before to after 2 h of digital device use, measured by a visual analogue scale.

8.11.2.3.3. Omega-3 fatty acid supplements. Two studies [572,573] by the same research group investigated oral omega-3 fatty acid supplementation and both found a significant improvement in digital eye strain symptoms at 6–12 weeks of follow-up (Fig. S1); however, results were unable to be pooled due to high heterogeneity. Drop-out rate in both studies was low (~5%), although one study did use last-observation-carried-forward approach for missing data [572], a potentially inappropriate technique given that symptoms scores tend to change over time. An additional trial studied the effect of a combined omega-3 and anti-oxidant supplement [583], but did not report significant differences in any relevant secondary outcome measures (eye

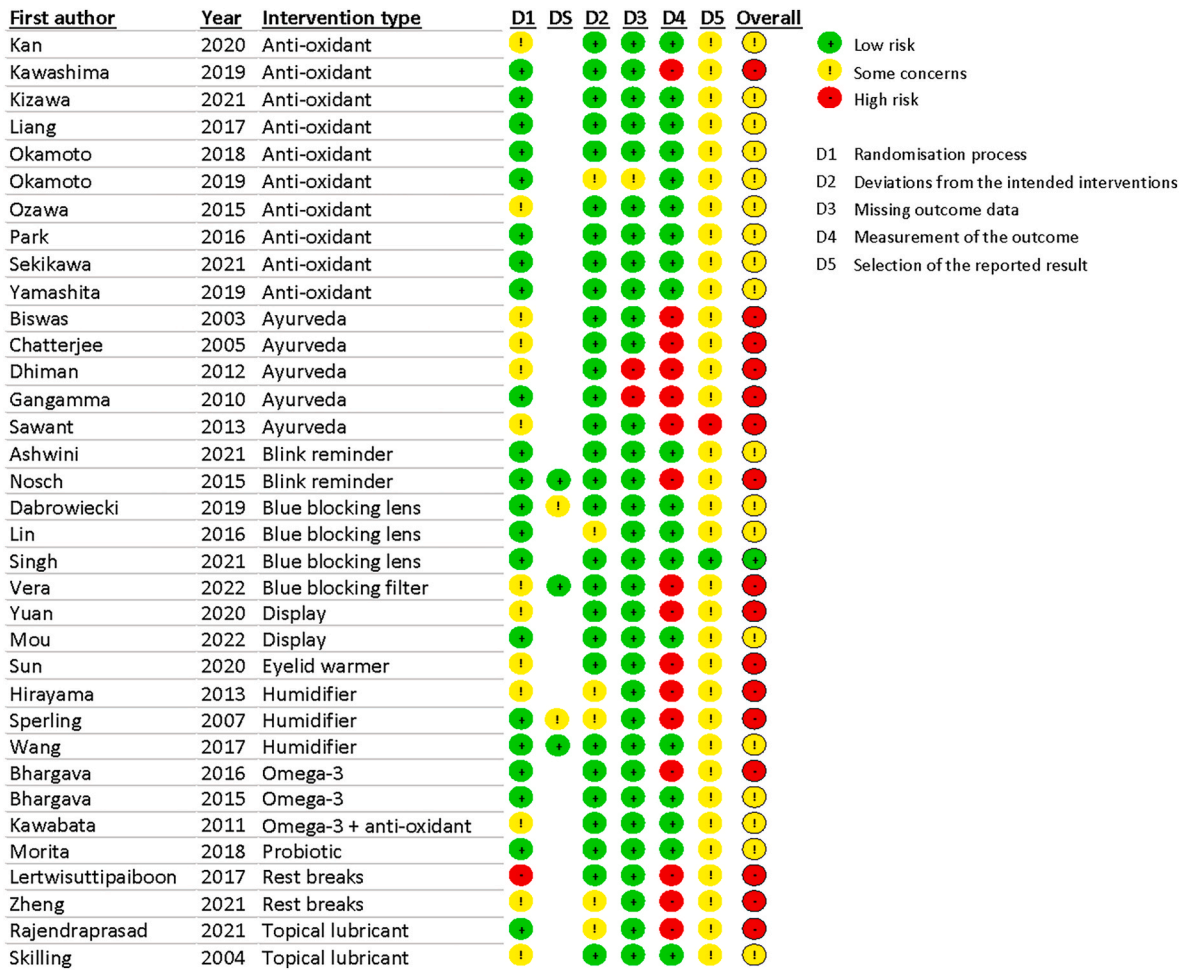

Fig. 7. Cochrane Risk of Bias 2 tool gradings for all included studies, ordered by intervention type. D1 is domain 1, D2 is domain 2 etc. Domain S applicable only for cross-over studies.

fatigue, dryness and redness) between the intervention and placebo groups.

8.11.2.3.4. Topical lubricants. Two head-to-head randomized controlled trials [604,605] compared topical lubricant eye drops for treating digital eye strain. In an open-label study [604] of topical carboxymethyl cellulose 0.5% versus topical hydroxypropyl methylcellulose 0.3%, participants using carboxymethyl cellulose 0.5% had a lower mean Ocular Surface Disease Index score after 15 days (mean difference = −0.83, 95% CI: −1.56, −0.10), 30 (mean difference = −1, 95% CI: −1.88, −0.12) and 90 days (−0.91, 95% CI: −1.71,- 0.11). However, the effect (a 1-unit difference in Ocular Surface Disease Index score) is unlikely to be clinically meaningful. Another study compared the topical lubricant polysorbate-80 0.5% to topical tetrahydrozoline hydrochloride and found no difference in the proportion of participants reporting visual comfort as "very comfortable" in polysorbate-80 compared to the tetrahyrodozoline hydrochloride group (odds ratio: 1.23, 95% CI: 0.63, 2.42) [605].

8.11.2.3.5. Blue light-blocking lenses. Four studies investigated the effect of blue light-blocking lens or screen filters on symptoms of digital eye strain. One study did not report outcome results in a format that could be extracted, but the remaining three studies reported data eligible for inclusion in the meta-analysis of primary or secondary outcomes. Overall, risk of bias was evaluated as low for one study [351], as some concerns for two studies [444,549], and high risk for the remaining study [555] (funnel plots in Fig. S3). There was no significant effect of blue light-blocking lenses on the primary outcome (Fig. 8) or secondary outcomes of eye strain or fatigue or glare (Fig. 10), dryness, burning or watering or tearing [351], with the exception of itching, which was assessed only in one study and found to be lower (more comfortable) in the blue light-blocking group (standardized mean differences = -0.98, 95% CI: −1.71, −0.25) [444]. Two studies assessed the effect of blue light-blocking lenses on blurring of vision and both had findings potentially consistent with no effect; however, the effect estimate of one favored the intervention while the other favored the comparator (Fig. 10) and these results were not pooled due to this heterogeneity. Data could not be extracted from one study [555], but it reported no significant change in eye tiredness after a 30 min reading task between the blue light filter and no blue light filter conditions. The certainty of evidence was assessed as low for eye strain or fatigue and very low for blurring of vision and glare.

8.11.2.3.6. Blink reminders. Two studies investigated the effect of blink reminder interventions on digital eye strain [515,516]. The intervention in both studies consisted of software that presents a reminder to blink when using a digital device at specified intervals (4 and 8 presentations/min). Blink reminder interventions were not estimated due to high heterogeneity. One study had an effect estimate consistent with no effect [516], while the other found a significant improvement in dry eye symptoms (Fig. 10), but was also judged to be at high risk of bias [515]. Data on secondary outcomes were not available.

8.11.2.3.7. Rest breaks. Two studies promoted rest breaks in an effort to reduce digital eye strain or feelings of stress [606,607]. Neither was able to mask participants from their assigned intervention group. One [606] used a live streaming app to encourage children to take breaks from digital device use during online schooling. Square

Table 7
Grading of Recommendations, Assessment, Development and Evaluation (GRADE) [598] assessments for the certainty of the body of evidence, for interventions for managing digital eye strain.

Intervention	Outcome	GRADE certainty	Reason for downgrading
Anti-oxidant supplements	Dry eye or digital eye strain symptom score	⊕⊖⊖⊖ Very low	Downgraded by three levels due to risk of bias (one study had overall high risk of bias and three studies had overall some concerns) and inconsistency (high heterogeneity)
	Eye strain or fatigue	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had overall high risk of bias and eight studies had overall some concerns)
	Dryness	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had overall high risk of bias and six studies had overall some concerns)
	Foreign body sensation	⊕⊖⊖⊖ Very low	Downgraded by three levels due to risk of bias (one study had overall high risk of bias and one study had overall some concerns) and imprecision (small sample size)
	Itching	⊕⊖⊖⊖ Very low	Downgraded by three levels due to risk of bias (one study had overall high risk of bias and one study had overall some concerns) and imprecision (small sample size)
	Watering or tearing	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had overall high risk of bias and five studies had overall some concerns)
	Eye redness	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had overall high risk of bias and three studies had overall some concerns)
	Blurred vision	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had overall high risk of bias and six studies had overall some concerns)
	Glare	⊕⊖⊖⊖ Very low	Downgraded by three levels due to risk of bias (one study had overall high risk of bias and four studies had overall some concerns) and inconsistency (estimated effects consistent with both no effect and favouring treatment)
Blue light-blocking lenses	Dry eye or digital eye strain symptom score	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had some concerns in the risk of bias assessment) and imprecision
	Eye strain or fatigue	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had some concerns in the risk of bias assessment) and imprecision (wide pooled confidence interval)
	Blurring of vision	⊕⊖⊖⊖ Very low	Downgraded by three levels due to risk of bias (one study had overall some concerns), inconsistency (high heterogeneity) and imprecision (wide confidence intervals)
	Glare	⊕⊖⊖⊖ Very low	Downgraded by three levels due to risk of bias (both studies had overall some concerns) and imprecision (small pooled sample size).
Blink reminders	Dry eye or digital eye strain symptom score	⊕⊖⊖⊖ Very low	Downgraded by three levels due to risk of bias (one study had overall high risk of bias and one had overall some concerns) and imprecision (small sample size)
Omega-3 fatty acids	Dry eye or digital eye strain symptom score	⊕⊕⊖⊖ Low	Downgraded by two levels due to risk of bias (one study had overall high risk of bias and one had some concerns).

root-transformed digital eye strain symptoms were significantly lower in the intervention, compared to the no intervention, group after 2 weeks (mean difference = −0.15, 95% CI: −0.28, −0.02). The other developed an eye care training program to encourage office workers to take regular rest breaks during device use [607]. At 4 and 8 weeks after the eye care training, the proportion of participants reporting eye strain symptoms was lower in the intervention group, compared to the no intervention group (intervention vs control group, week 4: odds ratio = 0.11, 95% CI: 0.03, 0.31; week 8: odds ratio = 0.10, 95% CI: 0.03, 0.29).

8.11.2.3.8. Humidifiers. Three studies investigated interventions aimed at increasing humidity in the environment or around the eyes [525,526,530]. In one study that used a moist cool air device, self-reported eye dryness assessed by Visual Analogue Scale was improved from baseline in the intervention group after 5 days, but was not significantly different to the placebo group (mean difference = −1.2, 95% CI: −4.0, 1.6) [525]. In a second study, after 1 h using a desktop Universal Serial Bus (USB) humidifier (increased humidity by 5%), participants in the intervention group were more likely to report an improvement in subjective comfort (odds ratio = 12, 95% CI: 2.6, 56.3) and less likely to report a decrease in subjective comfort (odds ratio = 0.08, 95% CI: 0.02, 0.30) [526]. A third study used microenvironment glasses, spectacles with periorbital gaskets that isolate the ocular surface from the surrounding environment, leading to higher humidity immediately surrounding the ocular surface [530]. After 30 min of digital device use by symptomatic digital device users, use of the microenvironment glasses was associated with a slightly lower Ocular Surface Disease Index scores (i.e. better comfort), compared to no treatment (mean Ocular Surface Disease Index score: 1.68 vs 2.63, respectively, $p < 0.05$). However, participants were not masked to treatment assignment and the standard deviation and the scale of the results was not reported. In the two studies reporting mean differences, the effect size of the intervention was small and unlikely to be clinically substantial. The study of a desktop USB humidifier found a large effect size for improvement in comfort, but a more nuanced understanding of the effect of the intervention could be gained by assessing comfort on a continuous scale, rather than a dichotomous scale.

8.11.2.3.9. Eyelid warming. One study [529] investigated the use of an eyelid warming steamer, a device that generates heat and steam over the eyelids, on digital eye strain symptoms. Dry Eye-related Quality of Life Score was found to improve after 2 weeks of treatment, but was not significantly different to the placebo group (device of same appearance that didn't generate heat) at the 2-week visit (mean difference = −6.1 [favors intervention], 95% CI: −14.5, 2.3).

8.11.2.3.10. Display type. One study examined the impact of an E-paper display on digital eye strain [84]. Compared to the control intervention (organic light-emitting diode display), participants in the intervention group had a lower Ocular Surface Disease Index score

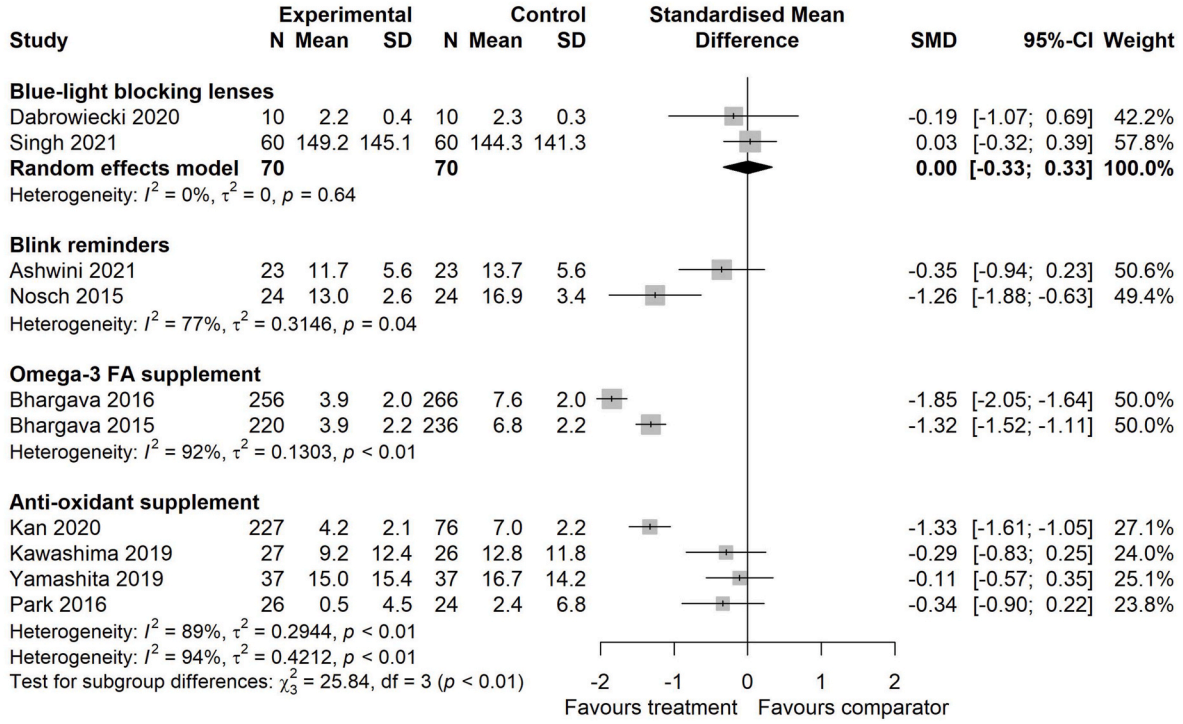

Fig. 8. Forest plot of results of digital eye strain or dry eye symptom summary score meta-analysis, sub-grouped by intervention type. Only data from the 12 studies reporting an eligible summary score are included. Eligible summary scores were also reported by single studies for parabiotic supplement, promotion of rest breaks, non-light-emitting display and eyelid warming steamer interventions. The tool used for symptoms assessment varied between studies (see Table 6). Only one study was conducted on a single day [351], and in all other studies the intervention was applied for multiple days (up to 90 days). Pooled analyses were not estimated where there was considerable heterogeneity ($I^2 \geq 75\%$). SD: standard deviation; SMD: standardized mean difference; CI: confidence interval; FA: fatty acid.

(mean difference = −5.17, 95% CI: −9.02, −1.32) and Computer Vision Syndrome Questionnaire score (mean difference = −8.15, 95% CI: −13.06, −3.24) after a 2 h reading task. In a similarly designed study [608], change in CVSS17 and Ocular Surface Disease Index scores were compared after a 2 h smart phone task using circularly or linearly polarized light-emitting displays. Change in both the CVSS17 score (mean difference = −3.70, CI: 5.00, −2.40) and Ocular Surface Disease Index score (mean difference = −5.21, CI: −6.93, −3.49) was lower in the circularly polarized display group after the 2 h task.

Results from these studies were not combined due to differences in the specific intervention; however, both indicate that non-conventional display types reduce symptoms of digital eye strain and dry eye, compared to conventional smart phone display types. In both studies, tasks were completed using either the experimental or control display in light and dark ambient lighting, separately, but these subgroups were combined for this analysis.

8.11.2.3.11. Ayurvedic therapy. Ayurveda is a traditional medicine originating in India. Five studies [590,591,593,595,601] investigated the impact of ayurvedic therapies on digital eye strain. Investigated therapies consisted of eye drops or oral capsules containing herbal extracts or the application of warm ghee (clarified butter) to closed eyes, while the patient periodically blinked. Data from all studies were unable to be included in the meta-analysis, either due to a lack of information about the method of outcome assessment, or the quantified outcome being categorical. All studies using ayurvedic therapy were judged to be at high risk of bias due to lack of information on, or absence of, masking of participants.

Three studies [590,591,601] reported the effect of herbal eye drop use on secondary outcomes. After 6 weeks of eye drop use, significant improvements were reported in symptoms scores of foreign body sensation (mean difference = −0.69, 95% CI: −0.93, −0.45 [601]; mean difference = −0.69, 95% CI: −1.00, −0.38 [591]) and eye redness (mean difference = −0.56, 95% CI: −0.78, −0.34 [601]; mean difference = −1.02, 95% CI: −1.37, −0.67 [591]), relative to placebo groups. Further improvements were found in eye watering symptoms after 6 weeks of eye drop use in the second study (mean difference = −0.42, 95% CI: −0.68, −0.16) [601]. A third study reported a significant difference in the number of participants reporting an improvement (dichotomous yes/no variable) in symptoms of blur (odds ratio = 4.3), glare (odds ratio = 6.3) and eye strain (odds ratio = 6.7) after 30 days of eye drop use, relative to the placebo group [590]; CI were not estimated for this study due to uncertainty around sample size. In a second intervention arm combining use of herbal eye drops and an oral herbal supplement for 30 days, the same study [590] reported improvements in blur (odds ratio = 12.0), glare (odds ratio = 7.4), eye strain (odds ratio = 8.3), burning sensation (odds ratio = 3.1), dryness (odds ratio = 2.9) and tearing (odds ratio = 5.9).

Two studies using topical ghee therapy also generally reported improvements in symptoms [593,595]. Using a 4-point scoring scale, one study found improvements in dryness (mean difference = −1, 95% CI: −1.26, −0.74), redness (mean difference = −0.67, 95% CI: −0.97, −0.37) and burning sensation (mean difference = −0.77, 95% CI: −1.14, −0.39) with topical ghee therapy, compared to no treatment [595]. Another study using topical ghee therapy [593], found no significant improvement in blurring of vision, redness, burning sensation or dryness between participants receiving either topical ghee or topical ghee in combination with an oral herbal supplement, compared to the control group; likely because samples sizes were small (n < 10 in each group). Eye strain was significantly better in participants receiving topical ghee and an oral herbal supplement (mean difference = −0.78, 95% CI: −1.15, −0.11), compared to the control group (receiving counselling on lifestyle changes), but was not significantly different in the group receiving topical ghee alone (mean difference = −0.63, 95% CI: −1.26, 0.01).

8.11.2.4. Subgroup analyses. Pre-specified sub-group meta-analyses

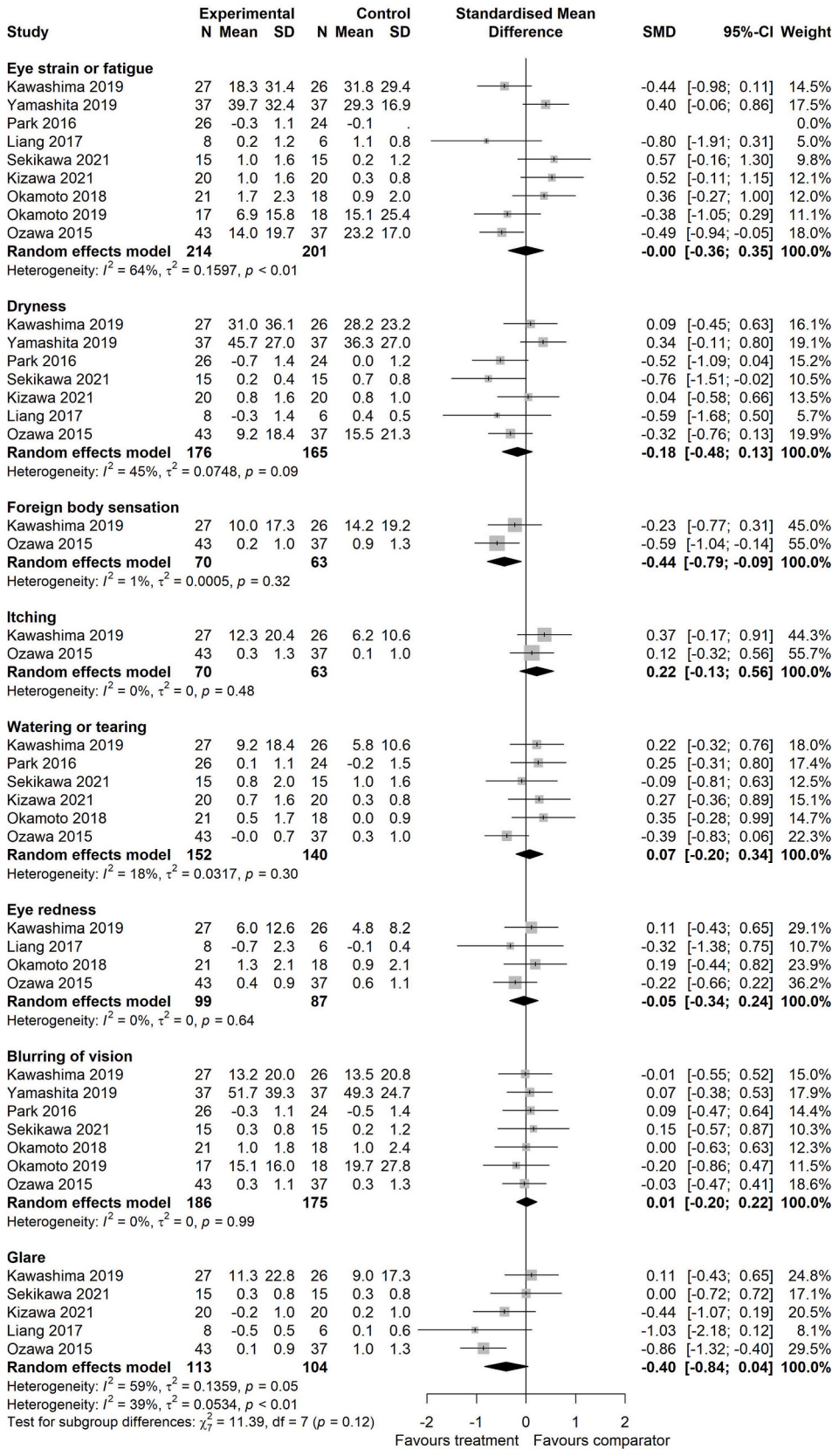

Fig. 9. Forest plot of secondary outcome measures in studies using an anti-oxidant supplement as the intervention. Data from 9 studies with eligible secondary outcome data were included. Only one study investigated the outcome of burning sensation and was not included in the meta-analysis [577]. Pooled analyses were not performed where there was considerable heterogeneity ($I^2 \geq 75\%$).

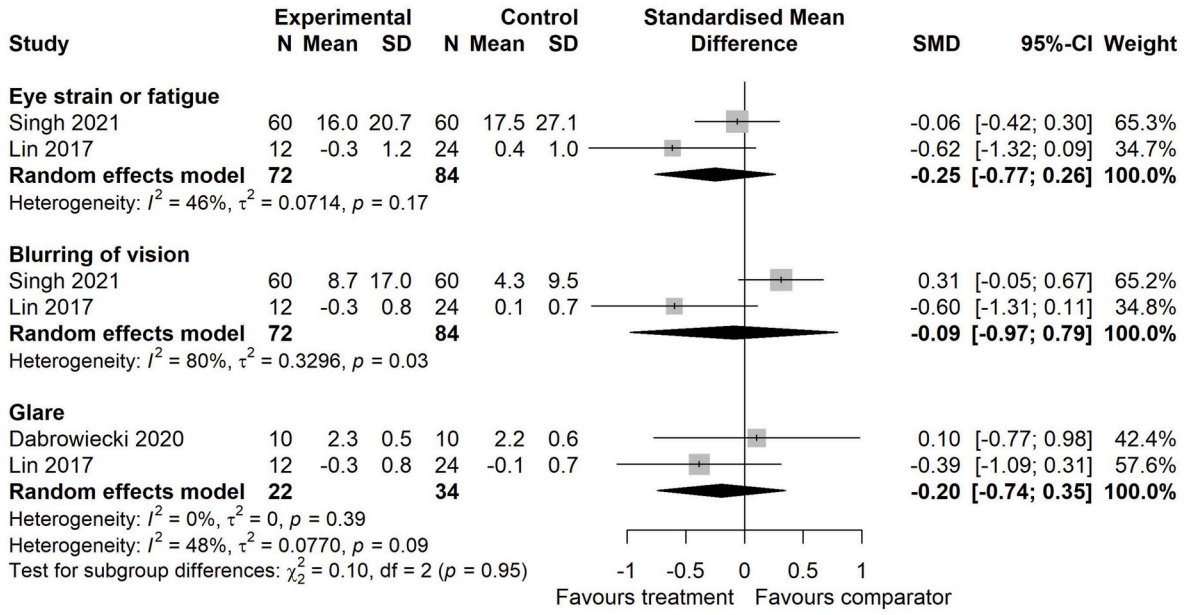

Fig. 10. Forest plots of studies investigating the effect of blue light-blocking spectacle lenses on symptoms of digital eye strain. One study was conducted over 5 days [549], while all other studies were ≤2 h. One additionally reported data on symptoms of dryness, burning sensation and watering or tearing [351], and another reported data on itching [444]. Pooled analyses were not performed where there was considerable heterogeneity ($I^2 \geq 75\%$).

were not performed on children and adolescents vs adults, and placebo vs no treatment comparator, as there were too few studies (≤1 in each intervention type) with eligible data studying a child and adolescent population or using no treatment as a comparator.

8.11.3. Systematic review discussion

This systematic review and meta-analysis sought to determine which ocular surface disease interventions can reduce symptoms of digital eye strain. Overall, there was low certainty that oral omega-3 fatty acid supplementation was associated with more favorable digital eye strain or dryness symptom scores (primary outcome), compared to control groups, with effect sizes for these interventions estimated to be around a 1.3 to 1.8 standard deviation improvement in symptom score, which approximates to a 10- to 13-unit lower (fewer symptoms) CVS-Q score, and would be considered a clinically meaningful effect. Blue light-blocking lens use was not associated with improvements in digital eye strain symptoms on pooled analysis. Results of studies on blink reminder software varied from no effect to favoring the blink reminder intervention (approximately a 10-unit improvement in CVS-Q score), with an overall very low certainty of evidence. Digital eye strain or dry eye symptoms scores were also reported in studies using a parabiotic supplement, humidifiers, an eyelid warming device, non-conventional display types and an app to promote rest breaks, but did not meet the criteria for data extraction or inclusion in the meta-analyses due to a lack of studies using the same intervention or outcome data not meeting the criteria for extraction. It is worth noting that the two non-conventional display types (E-paper and circularly polarized light-emitting displays) both demonstrated favorable results, compared to conventional displays, and so changing display type may show some promise for decreasing symptoms of digital eye strain.

It is perhaps easier to draw conclusions on interventions that do not appear to be effective for treating digital eye strain. Three of four studies using an anti-oxidant supplement did not identify a significant treatment effect on the digital eye strain or dry eye symptoms, while the remaining study found that symptoms in the intervention group were approximately 1.3 standard deviations lower (approximately 9.7 CVS-Q units) than the control group. This latter study used a much higher anti-oxidant dose of, on average, 2,800 mg/day (2–20 times higher than other studies) and this may have contributed to the high heterogeneity for the primary outcome and the overall certainty of evidence was assessed as low. Pooled analysis of the results of ten studies using an anti-oxidant supplement as their intervention and reporting secondary outcome data revealed no significant treatment effect for any secondary outcomes, with the exception of foreign body sensation, for which data from only two studies were available. Given that the majority of anti-oxidant studies find no significant treatment effect on digital eye strain symptoms, including on pooled analysis, it seems likely that this intervention has minimal impact on digital eye strain symptoms. Oxidative stress has been linked to dry eye disease [609] primarily through animal model work, but oxidative stress may not play the same role in causing symptoms of digital eye strain. Only one [444] of four studies investigating blue light blocking lenses or screen filters reported results favoring the experimental intervention and then only in relation to eye pain, heaviness or itchiness. All pooled analyses were consistent with no significant effect of blue blocking lenses as were all unpooled results from the remaining three studies [351,549,555]; hence on balance it would appear that blue blocking lenses or screen filters do little to attenuate symptoms of digital eye strain.

8.11.4. Strengths and limitations

Strengths of this review include a comprehensive literature search of two large medicine and health science databases, quality appraisal using the validated Risk of Bias 2 tool, targeting populations with digital eye strain or who had symptoms that worsened during digital device use, the use of strict criteria for inclusion in the meta-analysis and use of standardized mean differences allowing combination of treatment effect estimates from studies using different measurement tools. Limitations of this review include significant variation in the assessed study methods, including administration of the intervention and the measurement and reporting of digital eye strain symptoms. While this was expected, it nevertheless limits the ability to draw clear conclusions on the efficacy of most interventions and limited the ability to conduct pooled analyses. Due to corresponding heterogeneity, the digital eye strain symptom and dry eye symptom outcomes were merged, which may make the findings less applicable to digital eye strain itself and more applicable to dry eye symptoms during digital device use. However, given that studies recruiting patients with digital eye strain or assessing symptoms during device use were targeted, and that digital eye strain and dry eye

symptoms are correlated [29], it is likely that the findings remain relevant to digital eye strain.

9. Summary and recommendations

This report has clarified the terminology relating to the ocular effects of the digital environment (defined as any technology requiring viewing of a digital display for a cognitive task) with 'digital eye strain' being the preferred description. 'Digital eye strain' was defined as "the development or exacerbation of recurrent ocular symptoms and/or signs related specifically to digital device screen viewing" (Section 1). Digital technologies continue to evolve at a rapid pace and some of the early concerns around refresh rates, resolution and blue light emission have largely been overcome or shown to have limited impact on the visual system (Sections 2 and 3). While digital eye strain prevalence of up to 97% has been reported in specific populations (Section 4), prior to an agreed definition and with a lack of recognized diagnostic criteria, this will include individuals whose eye strain is not just digitally related and therefore should not be termed digital eye strain. However, eye strain when performing tasks reliant on a digital environment can cause discomfort, affect productivity and quality of life (Section 7) and therefore clear, evidence-based management strategies and treatments need to be established (Section 8).

Even the most widely used questionnaires for digital eye strain do not establish that the definition stated above is met, and objective signs are not 'diagnostic' of digital eye strain nor validated as sensitive to the severity of the condition or its management (Section 5). Hence, there is an unmet need to develop a quick-to-administer, sensitive diagnostic questionnaire to establish whether an individual meets the definition of having digital eye strain so they can be managed appropriately. Differential diagnosis from established dry eye disease, refractive error or binocular vision anomalies should be included as evidence-based management strategies have been established for these disease/conditions and so targeted approaches can be established specifically for digital environments (Fig. 11).

The mechanism of action appears to be an exacerbation of ocular surface disease (mainly due to reduced blink rate and completeness), non-fully-corrected refractive error and/or underlying binocular vision anomalies, together with the cognitive demand of the task and differences in position, size, brightness and glare compared to an equivalent non-digital task (Section 6). However, longitudinal studies are yet to be conducted to assess whether effects are cumulative, whether there is a critical period and whether disruption of circadian rhythms for the spectral light output, play a role. As a metric, screen time alone doesn't capture the cognitive demand of the tasks which appears to be an important aspect of the digital environment, so both these aspects should be quantified as part of a patient's history and symptoms. The dependence on digital devices is growing, so promoting reduction of

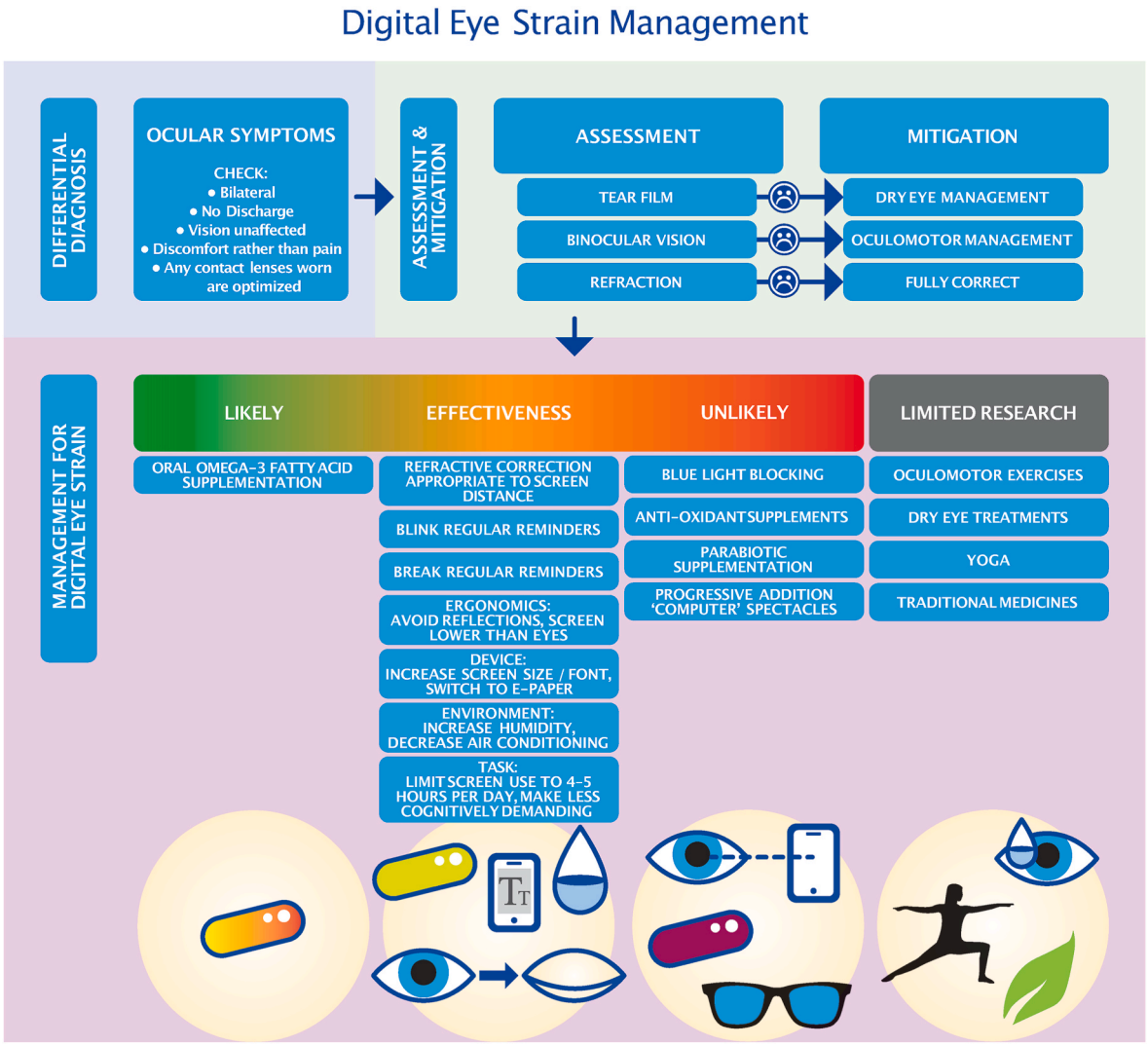

Fig. 11. Evidence-based management of digital eye strain schematic.

usage seems unlikely to be adopted, but there are implications in other areas of ocular development concern, such as myopic progression, that should be considered holistically. A different approach might need to be made in pediatric populations, who may be at a different level of risk given their early and prolonged adoption of digital technology.

In general, interventions are not well established and additional, longer duration, randomized controlled trials and subsequent meta-analyses are needed to select the most appropriate strategy for an individual. Patients suffering from digital eye strain should have a full refractive correction for the appropriate working distances. Improving blinking, optimizing the environment and encouraging regular breaks may help, but are yet to be established as effective, with further research needed (Fig. 11). Larger, high-quality, clinical trials are needed to robustly assess artificial tear effectiveness for relieving digital eye strain, particularly comparing different constituents; the use of secretagogues and warm compress/humidity goggles/ambient humidifiers looks promising, as does nutritional supplementation (e.g. omega-3 fatty acid supplementation and berry extracts). Based on current, best evidence, blue light blocking interventions do not appear to be an effective management strategy. Once the mechanisms of digital eye strain are better understood and evidence-based management options are better established, education of eye care practitioners and the public will be needed to ensure the productivity and quality of life of the population are optimized. Considering the ubiquitous use of digital technology, screening for digital eye strain should become incorporated into routine ocular assessments.

Although digital technology is generally considered to be detrimental to ocular health, there is also the opportunity to use technology to enhance patient eye health, with advanced user monitoring, counselling and treatment solutions. The potential of smart cameras to determine tear film stability has been demonstrated [610]. Apps and mobile notifications, for instance, can inform the patient when their contact lenses are due for replacement, or their eye drops need applying, aiding compliant behavior by the patient [611]. Alternatively, the patient-facing cameras in a virtual reality system [612] or mobile device can be used to monitor blinking characteristics [613,614] or to increase compliance with a minimum device viewing distance, for example by fading out the display when too close [215,615]. The high-quality camera and display systems integrated into mobile devices also allow remote image capture and management of patients, which has proved particularly useful during the COVID-19 pandemic. In the future, it may be possible to leverage the advantages of specific digital display systems, such as virtual reality or augmented reality to provide an environment which is anti-myopiagenic [616], or to provide warm humid micro-environments to minimize dryness symptoms [250,617]. These digital device systems are typically network-connected and enable such information to be reported directly back to the patient or onwards to their eyecare or medical practitioner, allowing ocular health to be carefully monitored and compliant behavior by the patient to be supported.

Declaration of competing interest

James S. Wolffsohn: 3m (F), AOS (C), Aston Vision Sciences (S), Atia Vision (C), Bausch & Lomb (C), Alcon (C,F), Allergan (F), CooperVision (C,F), CSIDryEye (C), DopaVision (C), Eyoto (S), Johnson & Johnson Vision (F), Rayner (F), M2C Pharmaceuticals (C,F), Medmont (C), Novartis (C,F), NuVision (C,F), Santen (C), Scope Ophthalmics (C,F), SightGlass (F, C), TFOS (S), Théa Laboratories (C,F), Topcon (F), The Eye Doctor (F), Veluon (F), Wolffsohn Research Limited (S), WO2019/001928 A1 (P), WO2019193051A1 (P).

Gareth Lingham: None (N).

Laura E. Downie: Alcon (F), Azura Ophthalmics (F), BCLA (R), CooperVision (F), Cornea and Contact Lens Society of Australia (R), Medmont International (R), NHMRC Australia (F), Novartis (F), TFOS (S), dry eye diagnostic method (P).

Byki Huntjens: Alcon (C), Bausch and Lomb (C), CooperVision (C), Johnson & Johnson Vision Care Institute (C).

Takenori Inomata: Novartis (F), Santen (F,C), Lion Corporation (F), SEED Company (F), Johnson & Johnson (F), Hogy Medical Co (F), Shin Nippon Biomedical Laboratories (F), Renatech (P), Kowa (P), InnoJin (E).

Saleel Jivraj: IMED Pharma (F, C), The Body Doctor (F), DryiRelief App (I), My Myopia Management App (I), Optometrist Calgary (P), Alcon (C).

Emmanuel Kobia-Acquah: None (N)

Alex Muntz: Azura Ophthalmics (F).

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Sotiris Plainis: None (N).

Michael Read: Johnson & Johnson Vision (F), Coopervision (C), Menicon (F), Visco Vision inc (F), US10959973B2 (P).

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Tor P. Utheim: ABIGO (F), Alcon (F,C), Allergan (F), AMWO (F), Bausch&Lomb (F), Bayer (F,C), European school for advanced studies in ophthalmology (F,C), InnZ Medical (F), Medilens Nordic (F), Medistim (F), Novartis (F,C), Santen (F,C), Specsavers (F,C), Shire Pharmaceuticals (F,C), Thea Laboratoires (F,C).

Jennifer P. Craig: Adelphi Values Ltd (R), Alcon (F,R,C), Asta Supreme (R), Azura Ophthalmics (F,R), E-Swin (F,R), Johnson & Johnson Vision (R), Manuka Health (F), Medmont International (R), Novoxel (R), Oculeve (F), Photon Therapeutics (R), Resono Ophthalmic (F,R), TFOS (S), Théa Laboratories (F,R), Topcon (F,R), TRG Natural Pharmaceuticals (F,R).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtos.2023.04.004.

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