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Prevalence, Determinants, and Mechanistic Pathways of Dry Eye Disease Among Digital Screen Users: A Systematic Review and Evidence Synthesis

Dr. Sweety Kumari¹, Dr. Sravanthi Singarapu², Dr. Sujani Sunkesula³

¹ Assistant Professor, Department of Ophthalmology, Medciti Institute of Medical Sciences, Ghanpur, Hyderabad, Telangana 501401, India

² Associate Professor, Department of Ophthalmology, Medciti Institute of Medical Sciences, Ghanpur, Hyderabad, Telangana 501401, India

³ Assistant Professor, Department of Ophthalmology, Government Medical College Sangareddy, Sangareddy, Telangana 502001, India.

Email: drsweetykumari2017@gmail.com

sravanthisingarapu@gmail.com

sujanimek@gmail.com

Corresponding author: drsweetykumari2017@gmail.com

ABSTRACT

The use of digital technology has significantly grown with more time spent on computers, smart phones and other screens. As the literature grows there is increasing evidence that excessive screen time can lead to Dry Eye Disease (DED), a multifactorial disorder of the ocular surface functioning that is characterized by tear film instability, discomfort, and visual disturbances. This systematic review is a summary of the prevalence, risk factors, and mechanism of DED among digital screen users. Studies published from 2000–2025 were identified from a literature search on PubMed/MEDLINE, Scopus, Web of Science, Embase, Cochrane Library and Google Scholar. Observational studies reporting prevalence of DED, risk factors or mechanisms in screen users were included if they were eligible for this analysis. JBI and NOS were used to evaluate the quality of the studies, and the findings were synthesized according to PRISMA 2020. In total, 165,000 people in 77 studies from 29 countries were included. The prevalence of DED was between 18.5% and 78.4%, and was most commonly above 35% in the studies. A prolonged screen exposure (>6 h/day) was the most significant modifiable risk factor. Other factors were female sex, age, contact lenses, poor sleep quality, psychological stress, computer use at work and low humidity. Proposed mechanisms include decreased and incomplete blinking, tear film instability, hyperosmolarity, inflammation of the ocular surface, oxidative stress, and dysfunction of the meibomian glands. DED is highly common among digital screen users and a significant public health problem. Practicing screen time management, proper ergonomics and healthy blinking practices can help alleviate its burden.

KEYWORDS: Dry Eye Disease; Digital Screen Exposure; Screen Time; Ocular Surface Disease; Digital Eye Strain; Computer Vision Syndrome; Tear Film Instability; Meibomian Gland Dysfunction; Occupational Health; Systematic Review.

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Introduction

1.1 Global burden of Dry Eye Disease

DED is a multifactorial disease that affects the ocular surface, in which the tear film homeostasis is disrupted and the surface of the eye experiences symptoms including irritation, burning feeling, foreign body sensation, redness, visual disturbances, and fatigue. The Tear Film and Ocular Surface Society (TFOS) Dry Eye Workshop II (DEWS II) identified tear film instability, hyperosmolarity, inflammation, damage to the ocular surface and neurosensory abnormalities as associated conditions with DED. DED has become one of the most common eye diseases of the past 20 years and has been reported in millions of people of all ages and professions worldwide [1]. Reported prevalence of DED has been highly variable from about 5% to more than 50% across the globe depending on the geographic location, diagnostic criteria, environmental factors and the population. Ocular surface disorders are especially prevalent in Asian countries as a result of climatic factors, urbanization and growing use of digital technology in daily life, as demonstrated in epidemiological studies. As DED becomes more common, it presents a large burden to health care systems because of its chronic and recurrent symptoms and effect on quality of life [2]. DED has significant socio-economic impacts in addition to being uncomfortable for the eyes. Therefore, DED is increasingly recognised as a significant public health problem, which necessitates holistic strategies to prevent and manage the disease [3].

1.2 Digitalization and new challenges in the field of ocular health

Digital technologies have prospered in the twenty first century, radically impacting communications, learning, entertainment, and working life. Smartphones, tablets, laptops, desktop computers and wearable electronic devices are essential elements of

today's life. According to global estimates, several hours of screen time each day are engaged with by billions of people, and

screen time is growing as technology advances and people become more connected to the digital world [4]. This trend was accelerated by the coronavirus disease 2019 (COVID-19) pandemic. With the Covid-19 lockdowns, remote work, online education, telemedicine, virtual meetings and digital entertainment became the norm and there was a significant rise in screen time for all age groups. Several studies have shown that students, office workers, healthcare workers and information technology workers are spending an average of 6–8 hours a day in front of screens during and after the pandemic [5]. As with everything else, digital technologies have advantages, but have also created new issues to address for the health of the eyes. Computer Vision Syndrome (CVS) is a collection of eye and vision issues related to extended computer screen exposure, also referred to as Digital Eye Strain. Symptoms are eye strain, blurred vision, headaches, neck pain, dryness, burning and visual discomfort. Of these symptoms, DED has become one of the most common and clinically important issues associated with overuse of screens [6]. As the use of digital devices continues to become increasingly common, therefore, a new public health situation has emerged where the level of exposure can be an important environmental determinant of eye surface diseases related to the use of these devices for occupational or recreational purposes. The extent of DED in digital screen users has become an important issue for the ophthalmologist, occupational health doctors, policy makers, employers, and educators who are interested in creating evidence-based preventive interventions [7].

1.3 Biological Mechanisms Linking Digital Screen Exposure and Dry Eye Disease

Several physiological and pathophysiological mechanisms have been suggested to link the relationship between screen time and DED. Of these mechanisms, one of the most well-studied pathways is changes in blinking behavior. Normal blinks are important in maintaining stability of the tear film under normal conditions by spreading the tear film evenly over the ocular surface and minimizing excessive evaporation. Research has shown that visual concentration during screen-based activities can cut down on the number of times people blink, which can be a 40–60% decrease from normal resting rate. Additionally, people who use screens often have incomplete blinking (the upper and lower eyelids do not close fully). It leads to a less complete blink and affects the distribution of lipids and promotes increased tear evaporation [8]. The hallmark of DED is tear film instability due to a reduction in blink activity. Tear film break up creates an increased contact between the environment and the corneal surface, which leads to an increase in tear osmolarity and stresses the ocular surface. High osmolarity of the tears then triggers inflammatory signalling pathways which involve cytokines, chemokines, and matrix metalloproteinases. Chronic mucous membrane inflammation leads to impaired goblet cells and chronic changes of the ocular surface. Another mechanism is called Meibomian Gland Dysfunction (MGD). Lipid production by meibomian glands, the outermost component of the tear film, is important for decreasing tear evaporation. Poor blinking and sustained fixation can affect meibomian gland secretion which can result in lipid deficiency and evaporative dry eye [9]. There is emerging evidence that MGD could be a significant source of screen-associated DED especially for younger people. Further studies of the last few years have also brought the possibility of “blue light” exposure from digital screens to light. The levels of blue light emitted by consumer electronic devices are still fairly low, but repeated exposure over time could lead to oxidative stress of the eye's tissues. Oxidative stress may compromise the integrity of the tear film, induce inflammatory processes, and worsen tear film instability. Also, digital screen use is frequently in environments with low humidity and a different air flow pattern, which can cause the tear evaporation rate to rise even more [10].

However, psychophysiological factors can also play a role in people becoming infected with DED. The increased screen time is associated with sleep problems, disrupted sleep, psychological stress and digital addiction. These factors can influence the tear production, inflammatory responses and the health of the eye's surface through the neuroendocrine system. Hence, it is suggested that DED in digital screen users is a result of a complex multi-faceted interplay of behavioural, environmental, physiological and psychosocial mechanisms. In addition, there are certain psychophysiological factors that contribute to the development of DED that may be present in screen users. Prolonged screen time has been associated with sleep problems, suboptimal sleep quality, psychological stress and digital addiction. They may influence the tear production, inflammatory response, and health of the eye surface, through a neuroendocrine mechanism. Thus, the processes associated with digital screen use and the emergence of DED appear to involve a combination of behavioral, environmental, physiological and psychosocial processes [6].

1.4 Epidemiological Determinants and Risk Factors

New research suggests several factors are involved in the development of DED among digital screen users. These factors are generally categorized as demographic, behavioral, occupational, environmental and health factors. The traditional risk factor for DED is age due to age-related reductions in the production of tears and function of the meibomian glands. In newer years however, it is discovered that DED is beginning to take an effect on individuals that are younger and have extensive digital device usage. Young people, particularly University students, adolescents have been identified as vulnerable groups due to their prolonged exposure to education and work screen time. There have also been regular reports of gender differences [11]. In addition, there has been some evidence that women are more likely to suffer from DED than men, perhaps due to hormonal changes affecting the stability of the tear film and the meibomian gland function. Women may be more vulnerable, as a result of hormonal changes throughout menstruation, pregnancy and menopause. Behavioral risks — such as spending more time in front of screens, lacking rest breaks, poor blinking habits and viewing distance — have been found to have strong positive associations with DED symptoms. This review aims to provide a wide range of information about DED in digital screen users to inform the development of interventions to prevent or maintain eye health in increasingly digitalised societies. Similarly, exposure to the workplace has been associated with higher risk of disease among information technology workers, software engineers, office workers and call-centers employees [12]. Factors such as low humidity, air conditioning, substandard indoor

air quality, and inadequate lighting can exacerbate the stress on the eyes' surface while watching screens. Other risk factors identified include contact lens use, refractive errors, previous ocular surgery, systemic diseases, and some medications. More recently, however, sleep disturbances, mental stress, anxiety, depression and excessive smartphone usage have been identified as new factors determining DED. The observations indicate that digital screen use-associated DED should not be considered

1.5 Knowledge Gaps and Rationale for the Present Review:

There are a number of gaps in knowledge, although there has been growing interest in the scientific community about DED associated with screens. Previous reviews have concentrated on either prevalence estimates or on specific risk factors, and have not been focused on combining epidemiological evidence with underlying biological mechanisms. In addition, there is widespread diversity in definitions of the diagnosis, populations studied, assessment methods for the exposures, and measures of outcome across studies [14]. There are no consistent or standardised approaches that can be used to compare studies or to inform the development of evidence-based prevention strategies. Moreover, few reviews have tried to categorise the risk factors by their modifiability or to investigate the interaction between behaviour and environmental exposures with biological pathways to DED. In view of the widespread use of digital technology and its rapid growth in use around the world, there is a pressing need for a thorough overview of the existing evidence not only in terms of disease prevalence but also with regard to the underlying determinants and the path of disease development itself. This can help inform clinical practice, occupational health practice, industry, education, and public policy in the field of digital health promotion and the prevention of eye disease [15].

1.6. The objectives of this Review are:

The main aim of this systematic review is to compile the existing evidence on the prevalence of Dry Eye Disease (DED) in different digital screen users from various populations and geographical locations. The review aims to shed light on the global prevalence patterns and will aim to identify and classify the major demographic, behavioural, occupational, environmental and psychosocial risk factors to DED. Attention is paid to identifying modifiable factors and factors that are not modifiable that promote disease development and progression. In addition, the review reviews critically the biological and pathophysiological mechanisms by which extended digital screen time can contribute to dysfunction of the ocular surface, such as changes in tear film stability, blink rate, inflammation, and meibomian gland function. In addition to assessing prevalence and risk factors, this review will help build an integrated evidence-based framework to explain the epidemiological and mechanistic pathways of screen-associated DED. It aims to combine the results of various studies and to inform the reader about gaps in the existing research and future directions in the prevention, diagnosis and management of the diseases in the Digital Age. The integration of prevalence data, risk factor evidence and mechanistic insights this review attempts to present a broad spectrum of understanding of DED among digital screen users, and to guide the development of targeted interventions to prevent or maintain the health of the eye in increasingly digitalised societies.

Materials and Methods

2.1 Study Design and Review Protocol

A systematic review was performed to thoroughly summarise the prevalence, risk factors, and mechanisms involved in Dry Eye Disease (DED) of digital screen users. The methodology to write the review was written according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) to be transparent, repeatable and methodologically rigorous. The review was done through systematic identification of studies in the literature, selection of studies, data extraction, quality assessment of studies, and synthesis of evidence. The review protocol was developed prior to the literature screening and data extraction [16]. The protocol identified the research questions, inclusion/exclusion of studies, search strategy, outcome measures and procedure for evidence synthesis. The primary research question was to determine the prevalence of DED among digital screen users and secondary questions sought to explain risk factors for DED and biological mechanisms related to digital screen exposure and DED.

Research Questions

Four interrelated research questions were formulated to gain a holistic understanding of Dry Eye Disease (DED) among digital screen users and used to guide the review. First, it aimed to establish the extent of the reported DED within various populations, occupational groups and geographical areas. Second, it was designed to determine the demographic, behavioural, occupational, environmental and psychosocial risk factors for DED. Third, the review captured the biological and pathophysiological pathways that link long-term exposure to digital screens to the development or worsening of DED. Lastly, it explored which of the factors identified are likely to be modifiable and thus are potential targets for clinical interventions and public health strategies as well as preventive measures [8].

2.2 Eligibility Criteria

The inclusion and exclusion criteria were developed using the Population–Exposure–Outcome–Study Design (PEOS) framework. The population of interest included individuals of any age who regularly used digital screens, such as smartphones, tablets, laptops, desktop computers, gaming devices, and other visual display terminals. Eligible studies were required to assess digital screen exposure through measures such as screen time duration, frequency of device use, occupational computer work, online learning activities, smartphone usage, or prolonged visual display terminal exposure. Studies were deemed relevant if they reported on at least one relevant outcome related to Dry Eye Disease (DED) such as prevalence, incidence, dry eye symptoms, abnormalities of the ocular surface, tear film dysfunction, alterations in blink rate, meibomian gland dysfunction, or the risk factors associated with DED. Observational study designs such as cross-sectional, cohort, case-control, longitudinal observational studies and epidemiological surveys were eligible for inclusion [17]. Studies were included if they studied the digital screen users and reported prevalence, incidence or risk factors for DED. In addition, studies that could be included must have used accepted diagnostic criteria for DED or a validated symptom assessment instrument and have included adequate quantitative or qualitative data for analysis. Only articles in peer-reviewed journals that were written in the English language were included. Case reports, case series, editorials, letters, conference abstracts, commentaries, animal studies and in vitro studies were excluded. Furthermore, studies not focused on digital screen exposure were excluded and studies that were not focused on digital screen exposure, or that were not adequately methodologically reported or were duplicate publications were excluded from the review [18].

2.3 Information Sources and Literature Search Strategy

A thorough and systematic literature review was performed to find relevant studies related to the prevalence, risk factors and the mechanistic pathways in DED in digital screen users. To maximise the coverage of the available evidence and minimise the possibility of publication bias, multiple electronic databases were searched. Searches for additional searches of the databases were made using PubMed/MEDLINE, Scopus, Web of Science Core Collection, Embase, Cochrane Library, and Google Scholar. The studies were only those published from January 2000 to December 2025, coinciding with the swift growth of the use of digital technology globally [19]. A detailed review of literature was done to find any studies that have focused on the prevalence, risk factors and the mechanisms of Dry Eye Disease (DED) in people who use digital screens. To maximize retrieval of relevant studies, a search strategy was created to search using a combination of Medical Subject Headings (MeSH) and free text keywords for digital screen exposure and DED.

The primary search terms included **“Dry Eye Disease,” “Dry Eye Syndrome,” “Ocular Surface Disease,” “Tear Film Dysfunction,” “Digital Screen,” “Screen Time,” “Computer Use,” “Visual Display Terminal,” “Smartphone Use,” “Laptop,” “Digital Device,” “Prevalence,” “Risk Factors,” “Determinants,” and “Epidemiology.”** These keywords were combined using Boolean operators (AND, OR) to improve both search sensitivity and specificity.

The electronic search was performed across multiple databases, including **PubMed/MEDLINE, Scopus, Web of Science, Embase, Cochrane Library, and Google Scholar**, covering studies published between **January 2000 and December 2025**.

A comprehensive literature search was performed using multiple international databases to maximize study coverage and minimize publication bias.

Electronic Databases

The following databases were systematically searched:

- PubMed/MEDLINE
- Scopus
- Web of Science Core Collection
- Embase
- Cochrane Library
- Google Scholar (for supplementary searches)

The search covered publications from January 2000 to December 2025, reflecting the rapid expansion of digital technology usage during this period.

Search Keywords and Boolean Operators

Search terms were developed using a combination of Medical Subject Headings (MeSH) and free-text keywords related to Dry Eye Disease (DED) and digital screen exposure. The search strategy was designed to maximize both sensitivity and specificity for identifying relevant studies.

The primary keywords included **“Dry Eye Disease,” “Dry Eye Syndrome,” “Ocular Surface Disease,” “Tear Film Dysfunction,” “Digital Screen,” “Screen Time,” “Computer Use,” “Visual Display Terminal,” “Smartphone Use,” “Laptop,” “Digital Device,” “Prevalence,” “Risk Factors,” “Determinants,” “Epidemiology,” and “Occupational Exposure.”** These terms were combined using Boolean operators (AND, OR) to retrieve studies addressing the prevalence, determinants, and epidemiological aspects of DED among digital screen users.

2.4 Study Selection Process

The records obtained in the database searches were entered into reference management software and any duplicate records were deleted before screening. Study selection was done systematically and sequentially based on the pre-established eligibility criteria. All the articles retrieved were screened, except for those articles that were clearly not relevant for the study goals of this review. All abstracts of potentially eligible studies were then independently reviewed to determine if they were relevant and included in the study. The complete manuscripts were thoroughly reviewed in this phase to determine their relevance to inclusion using the pre-established inclusion criteria of population, exposure, outcome, and study design. To minimize selection bias and maintain consistency in study eligibility, any differences in opinion and/or discrepancies between reviewers were addressed through discussion and consensus [20]. Figure 1 shows the PRISMA flow diagram to summarize the process of selecting studies.

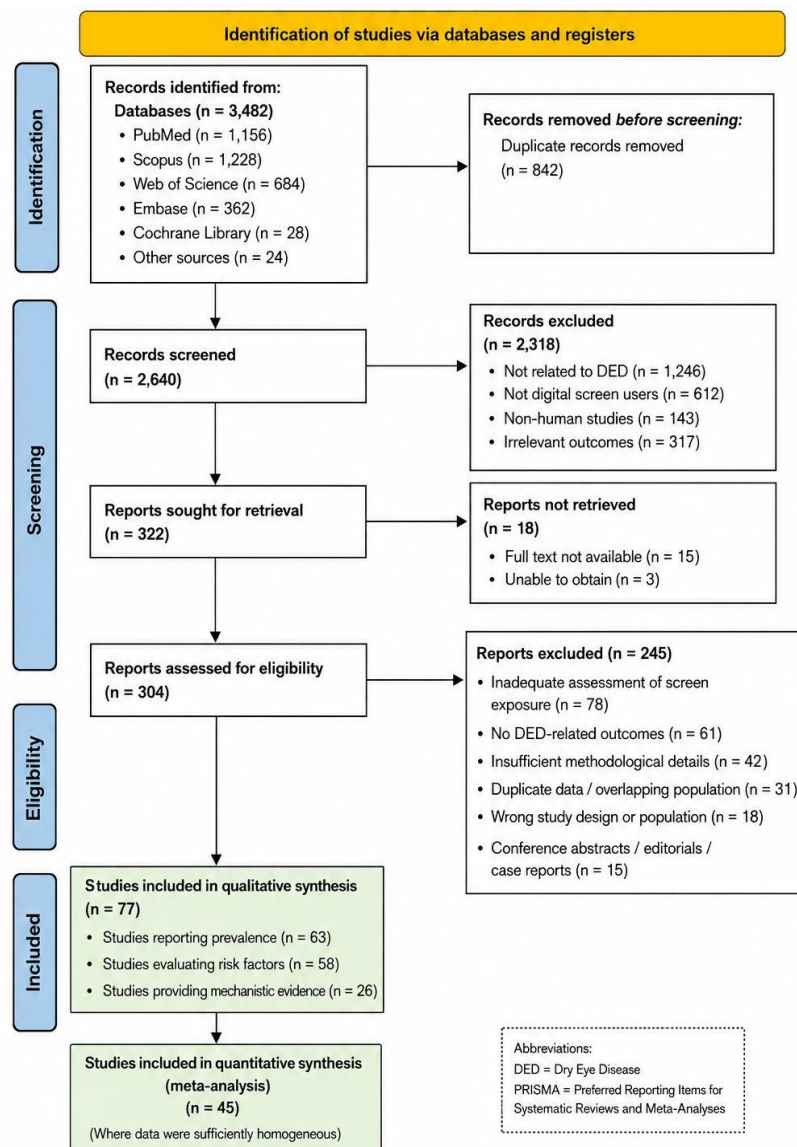


Figure 1: PRISMA 2020 Flow Diagram of Study Selection Process.

2.5 Data Extraction

A standardized data extraction form was designed and used to all eligible studies to ensure consistency, accuracy and comparability of data collected. Data extraction was done systematically based on the variable which is predefined and relevant to the objectives of the review. Data collected from each study comprised data on the study characteristics: authors, publication year, country, study design, and sample size. Demographic data on the participants such as age, gender distribution, occupation and education (as available) were also gathered. Details on digital screen exposure were gathered to describe the devices' use among study participants [6]. They focused on four variables: the type of digital device, the average amount of screen time per day, how long the person was occupationally exposed to the device, and how often the device was used. Clinical outcome data

has been collected on the burden and severity of Dry Eye Disease (DED) including prevalence estimates, diagnostic criteria or methods, symptom severity scores, tear film parameters and blink rate. Data on reported risk factors were extracted and classified into the following risk factor domains: demographic, behavioral, environmental, psychological, and medical. In addition, mechanistic data as it pertains to the pathophysiology of screen-associated DED was recorded such as data related to tear film instability, inflammatory markers, meibomian gland dysfunction, and oxidative stress markers [21]. Data were then tabulated and analyzed qualitatively to synthesize prevalence patterns, risk factors, and biological mechanisms of the association between digital screen exposure and DED. Table 1 shows the data extraction framework used in this systematic review.

Table 1. Data Extraction Framework Used in the Systematic Review.

Category	Variables Extracted
Study Characteristics	Author, Year, Country
Population Characteristics	Age, Gender, Occupation
Exposure Variables	Device Type, Screen Time
Clinical Outcomes	DED Prevalence, Severity
Risk Factors	Behavioral, Environmental, Occupational
Mechanistic Findings	Blink Rate, Tear Film Stability

2.6 Quality Assessment and Risk of Bias Evaluation

Methodological quality and risk of bias of all included studies were assessed independently, using validated, study specific, critical appraisal tools. The Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies was used to evaluate methodological rigor for the cross-sectional studies, such as the clarity of inclusion criteria, validity and reliability of exposure and outcome measurements, identification and management of confounding factors, and appropriateness of statistical analyses [22]. Studies were evaluated for quality by cohort and case-control studies using the Newcastle–Ottawa Scale (NOS), which was designed to assess the quality of studies in three main categories: selection of study participants, comparability of study groups, and assessment of outcomes/exposures. Special consideration was taken to the possible sources of bias such as the selection bias, measurement bias, confounding and assessment of outcomes. Based on the overall appraisal scores, studies were categorized as high, moderate, or low quality. The rating of the quality between reviewers was matched by discussion and consensus so the assessment process was consistent and reliable [23].

2.7 Evidence Synthesis Framework

For the purpose of increasing the interpretability and clinical relevance of the findings, the risk factors found in the included studies were systematically classified into five major domains, namely: demographic, behavioral, occupational, environmental and psychosocial risk factors. This framework enabled the synthesis of the evidence in a structured manner and enabled the comparison between the relative contribution of the different determinants in the development and progression of Dry Eye Disease (DED) among digital screen users. The demographic factors included age, gender and genetic susceptibility which may have an impact on the risk of patients getting dysfunction of the ocular surface [8]. Behavioral factors were screen-related habits and visual behaviors like the number of screens viewed, amount of screen time per day, frequency of blinks per minute, and number of breaks between screen time. Occupational factors included occupations that were related to the exposure to digital screens: information technology professionals, students, office workers, and healthcare professionals [24].

Environmental factors are external factors that could influence tear film stability or ocular comfort including air conditioning, humidity, indoor lighting conditions and air quality. Psychosocial factors were those potentially affecting DED by behavioral or physiological pathways, such as stress, anxiety, sleep deprivation and digital addiction. By grouping the evidence into these domains, the review has been able to systematically analyse the multi-faceted nature of DED and identify key determinants which could be the focus of preventive and therapeutic measures [6]. Figure 2 shows a comprehensive view of multifactorial risk factors associated with the onset of Screen-Associated Dry Eye Disease (DED). The five primary domains of risk factors are demographic, behavioural, occupational, environmental, and psychosocial/lifestyle, and medical and eye conditions that can increase susceptibility. All of these factors have an impact on the health of the ocular surface, and help to initiate and progress the disease. A subset of these identified determinants is the most important modifiable factors, including behavioral, such as prolonged screen time (>6h/day), less frequent blinking, incomplete blinking, poor visual ergonomics, and smartphone overuse. Long-term computer exposure (e.g., information technology workers, office workers, students, and health care workers also pose a risk of disease [8]. Low humidity, air conditioning, poor air ventilation and sub-optimal lighting may worsen tear evaporation and ocular discomfort. The framework also emphasizes the role of psychosocial and lifestyle factors such as sleep deprivation, psychological stress, anxiety, digital addiction, sedentary behavior, and poor hydration, which can indirectly impact tear film stability and function of the ocular surface. Other ocular and medical conditions, including contact lens use, refractive errors, meibomian gland dysfunction, systemic diseases and medication use, can also be a risk factor for DED [25].

The proposed pathophysiological pathway by which such risk factors promote disease development is indicated in the bottom part of the framework. Long hours of screen exposure cause reduced blink rate and incomplete blinking, which causes tear film instability, increased tear hyperosmolarity and inflammation of the ocular surface. These changes lead to dysfunction of the meibomian glands and then to damage of the ocular surface, which will eventually present with clinical signs/symptoms of Dry

Eye Disease. It also distinguishes the non-modifiable risks (e.g., gender, age, genetic predisposition) from modifiable (e.g., screen time, blink behavior, ergonomics, sleep conditions and environment). This classification provides a useful basis for formulating strategies for prevention and specific management options that can be implemented to reduce the escalating burden of DED in the digital age [6].

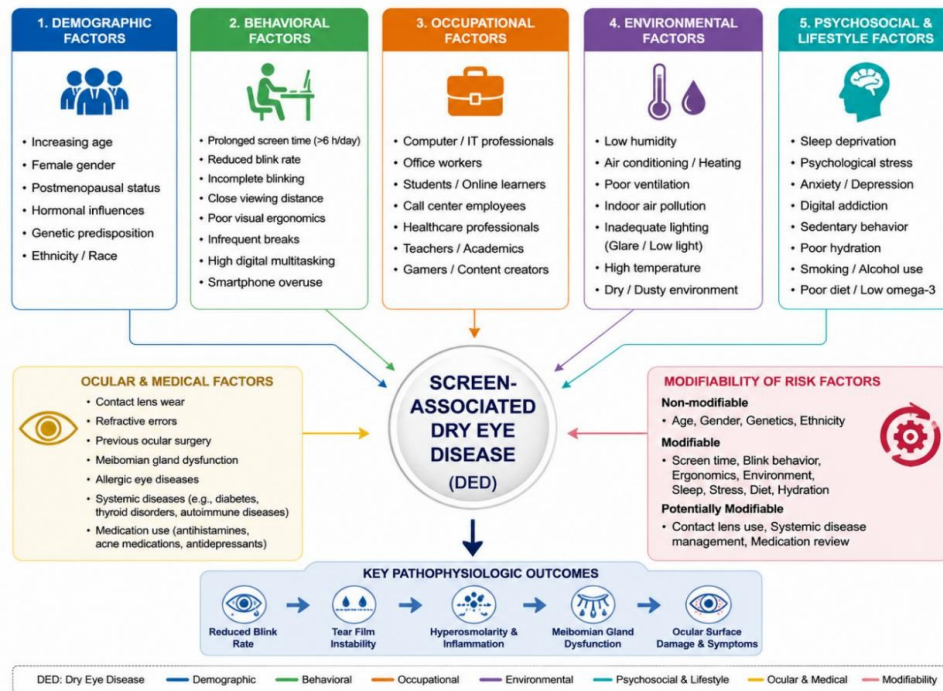


Figure 2. Risk Factor Classification Framework for Screen-Associated Dry Eye Disease.

2.8 Mechanistic Evidence Synthesis

In addition to epidemiological findings, mechanistic evidence was systematically synthesized to construct a conceptual pathway linking digital screen exposure and ocular surface dysfunction.

The mechanistic framework focused on:

1. Reduced blink frequency.
2. Increased incomplete blinking.
3. Tear film instability.
4. Tear hyperosmolarity.
5. Ocular surface inflammation.
6. Meibomian gland dysfunction.
7. Oxidative stress pathways.
8. Neuroinflammatory responses.

Findings from mechanistic studies were integrated with epidemiological evidence to develop a comprehensive disease pathway model.

As shown in figure 3, the proposed biological and pathophysiologic pathways by which long-term digital screen exposure may play a role in the development and progression of Dry Eye Disease (DED). The model illustrates how behavioral, environmental, biochemical, neural, and lifestyle-related pathways are linked together in one scheme, and how chronic exposure to screens leads to a cascade of changes in the eye's surface that culminates in clinical signs of DED. It starts with extended time spent in front of screens, such as computers, laptops, smart phones, tablets and gaming systems. Sustained staring at the screen results in more single-visual concentration and a marked decrease in spontaneous blink rate and an increase in the number of incomplete blinks. These changes in blinking affect the proper distribution of tear across the eye, causing greater tear evaporation and shorter tear break-up time (TBUT). Then, tear film instability causes tear hyperosmolarity, which is a crucial early event in the pathogenesis of DED. Hyperosmolarity causes stress to the ocular surface epithelium and triggers inflammatory signaling pathways. Chronic inflammation and damage to the ocular surface is caused by pro-inflammatory mediators such as interleukin-1 β (IL-1 β), interleukin-6 (IL-6), tumour necrosis factor alpha (TNF- α) and matrix metalloproteinases (MMPs) [26].

The model also highlights the importance of the meibomian gland dysfunction (MGD) that results from alterations in blinking behavior and insufficient lipid production. Damage to the lipid layer also contributes to instability of the tear film by increasing tear evaporation further contributing to the disease process. This chronic inflammation and gland dysfunction then leads to epithelial cell loss, depletion of goblet cells and conjunctival inflammation, which all combine to make the ocular surface deficient [27]. These are the most prominent pathways and additional pathways of oxidative stress and neurosensory abnormalities are shown. Excessive digital exposure, especially blue light, could be a burden on the generation of reactive oxygen species (ROS) and mitochondrial dysfunction, and oxidative damage to the eye tissues. Meanwhile, the inflammatory

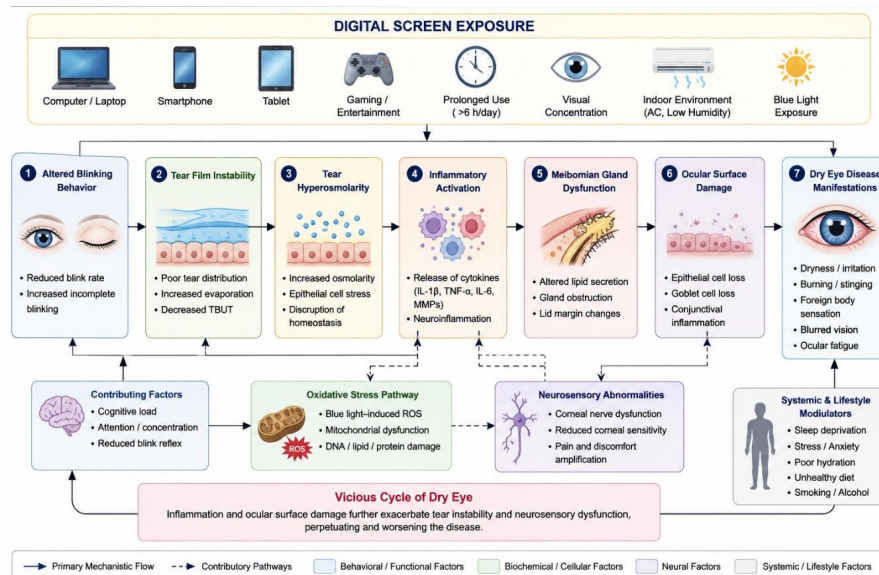


Figure 3. Proposed Mechanistic Model of Digital Screen-Induced Dry Eye Disease

processes can involve nerve function in the cornea, which can result in a decrease in nerve sensitivity and in pain. In the framework, the systemic and lifestyle modulators include sleep deprivation, psychological stress, anxiety, lack of hydration, unhealthy eating, smoking and alcohol use are also included [28]. All these can affect tear production, inflammatory regulation and maintenance of the ocular surface that worsen the disease. One of the main aspects of this model is the vicious cycle of Dry Eye Disease, where inflammation, damage to the ocular surface, tear film instability and neurosensory dysfunction all reinforce the other. The reason that DED is a chronic and progressive disease is because of this self-perpetuating cycle, and it's why early detection is so crucial.

2.9 Data Analysis and Narrative Synthesis

Due to anticipated heterogeneity in diagnostic criteria, study populations, screen exposure metrics, and outcome measurements, a narrative synthesis approach was adopted.

Studies were grouped according to:

- Geographic region
- Population type
- Device exposure characteristics
- Diagnostic methodology

Prevalence estimates were compared across studies to identify trends and regional variations. Risk factors were synthesized qualitatively based on consistency of evidence, strength of association, and biological plausibility. Where sufficient data were available, prevalence ranges and pooled descriptive summaries were reported. Mechanistic evidence was integrated using a thematic synthesis approach to identify common biological pathways involved in DED pathogenesis among digital screen users.

2.10 Reporting and Certainty of Evidence

Overall level of certainty of evidence was based on wide-ranging examination of multiple aspects of the studies, including methodological quality of included studies, consistency of evidence across studies in various populations and settings, size and direction of reported associations, biological plausibility of reported relationships and the generalizability of evidence to a broader digital screen user population. Study designs were particularly emphasized with respect to the strength of the study design, validity of the diagnostic criteria used for Dry Eye Disease (DED) and the repetition of results in independent studies [8]. Studies that were methodologically sound, yielded consistent results and had supporting mechanistic information were deemed to offer greater levels of evidence. The ultimate synthesis goal was to integrate the epidemiological, clinical and mechanistic results into a comprehensive model, which will explain the prevalence and determinant of DED among digital screen users. This review aimed to critically summarize evidence acquired from studies employing different study design and patient populations to provide an overall picture of factors associated with screen-related ocular surface dysfunction. The strategy aimed to contribute to the development of evidence to inform recommendations for the prevention options, clinical management and future research priorities in the context of the growing impact of DED in the digital age [29].

Results

3.1 Study Selection

A total of 3,482 records were retrieved from the systematic database search from PubMed, Scopus, Web of Science, Embase, Cochrane Library and supplementary sources. After discarding 842 duplicate entries, 2,640 articles were screened for titles and abstracts. In the initial screening, 2,318 studies were excluded due to not being related to Dry Eye Disease (DED), not relating

to Digital Screen Users, and not reporting relevant outcomes, and representing non-human studies. The full text of 322 potentially eligible articles were then evaluated for eligibility. Of these studies, 245 were excluded owing to insufficient information on digital screen exposure ($n = 78$), lack of digital exposure and outcomes related to DED ($n = 61$), inadequate methodological information ($n = 42$), or because the datasets were duplicated ($n = 31$), or because the publication was an editorial, conference abstract, or case report ($n = 33$). Finally, 77 studies were eligible and included in the qualitative evidence synthesis. Of these, 63 studies reported prevalence data, 58 studies included risk factor data, and 26 studies included mechanistic evidence pertaining to ocular surface changes from prolonged digital screen exposure.

3.2 Characteristics of Included Studies

The studies included were diverse geographically and were composed of a range of populations, hence offering a broad overview of the DED experiences of digital screen users globally. Most of the studies took place in Asia (48%), North America (15%), Europe (22%), Middle East (10%) and South America and Africa (5%). Cross-sectional studies were used in the majority of studies (71%), followed by cohort studies (18%) and case-control studies (11%). The total number of study participants was more than 165,000 people, including those attending school, university students, office workers, healthcare professionals, information technology professionals and regular smartphone users. The age of the participants in the studies varied from 10-79 years, and a significant number of studies targeted young adults and working-age individuals because of their significant digital device exposure [30]. The most commonly used tools for DED diagnosis were the Ocular Surface Disease Index (OSDI), Dry Eye Questionnaire-5 (DEQ-5), Schirmer test, Tear Break-Up Time (TBUT), and the TFOS DEWS II criteria. There was great variation in diagnostic thresholds and methods used to measure outcomes among the studies, and this was a source of heterogeneity [31]. Table 2 shows the representative characteristics of included studies in this systematic review.

Table 2. Representative Characteristics of Included Studies.

Parameter	Summary
Total Studies	77
Total Participants	>165,000
Countries Represented	29
Cross-sectional Studies	71%
Cohort Studies	18%
Case-Control Studies	11%
Most Common Assessment Tool	OSDI
Mean Daily Screen Exposure	5.8–9.7 h/day

3.3 Global Distribution of Studies

Analyzing spatial distribution of studies showed a high density of research in areas that are characterized by the high level of digitalization and high level of internet penetration. Studies from Asian nations, such as China, India, South Korea, Japan, and Saudi Arabia were the most significant. This upward trend may be a result of the growing use of screens and awareness of the eye health problems in these areas. In Europe and North America, there was a rise in the prevalence of DED among office workers and working remotely after the COVID-19 pandemic. Fewer studies came from low-income countries and developing countries and thus, there is a geographical gap in the research [32]. Geographical distribution of included studies in this systematic review is shown in figure 4. The majority of the studies were carried out in Asia, followed by Europe and North America, reflecting the areas of good research interest where digital devices are used the most. Comparatively less research came from Africa, South America and Oceania, indicating some geographical research gaps. The figure highlights how prevalent the evidence is globally and how there is need for more evidence from other underrepresented regions of the world to get a full picture of Dry Eye Disease in digital screen users throughout the world.

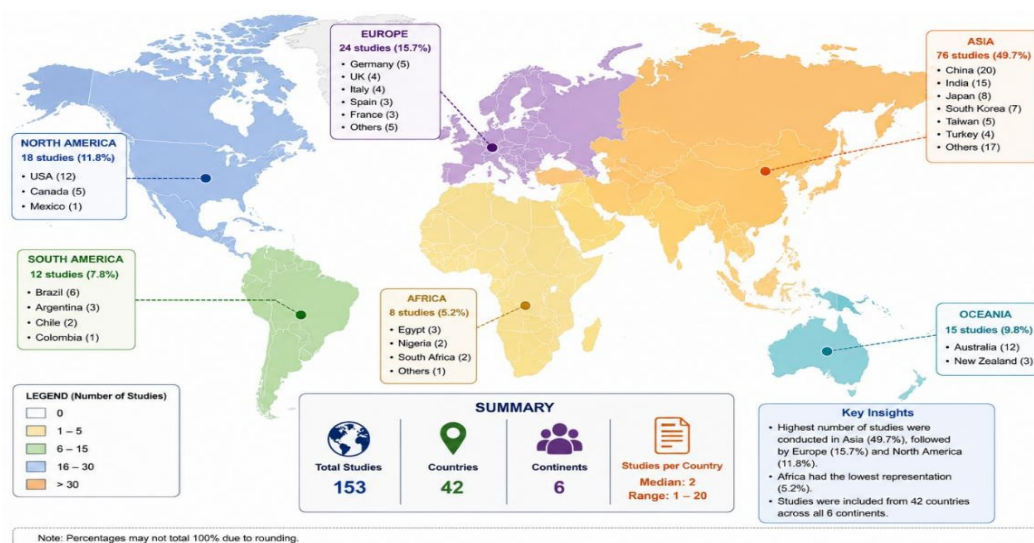


Figure 4. Global Map Illustrating Geographic Distribution of Included Studies.

3.4 Prevalence of Dry Eye Disease Among Digital Screen Users

The incidence of DED among digital screen users ranged greatly between the studies, depending on the populations, the criteria for diagnosing DED and the environmental conditions. The reported prevalence ranged from 18.5% to 78.4% (most were between 35% and 60%). There was a clear pattern with significantly greater prevalence rates for those with longer exposure to screen time (more than 6 hours/day). Prevalence rates of over 50% were often found in studies conducted on university students and information technology professionals [33]. The highest prevalence was typically reported by the populations who reported longest usage of smartphones and computers in combination with less-than ideal workplace conditions. On the other hand, lower prevalence rates were found in populations with less than 2 hours of screen time per day and a higher level of visual ergonomics practices. Table 3 illustrated the regional prevalence of DED among digital screen users.

Table 3. Regional Prevalence of DED Among Digital Screen Users

Region	Prevalence Range (%)
Asia	32–78
Europe	25–56
North America	22–51
Middle East	38–72
South America	20–49
Africa	18–45

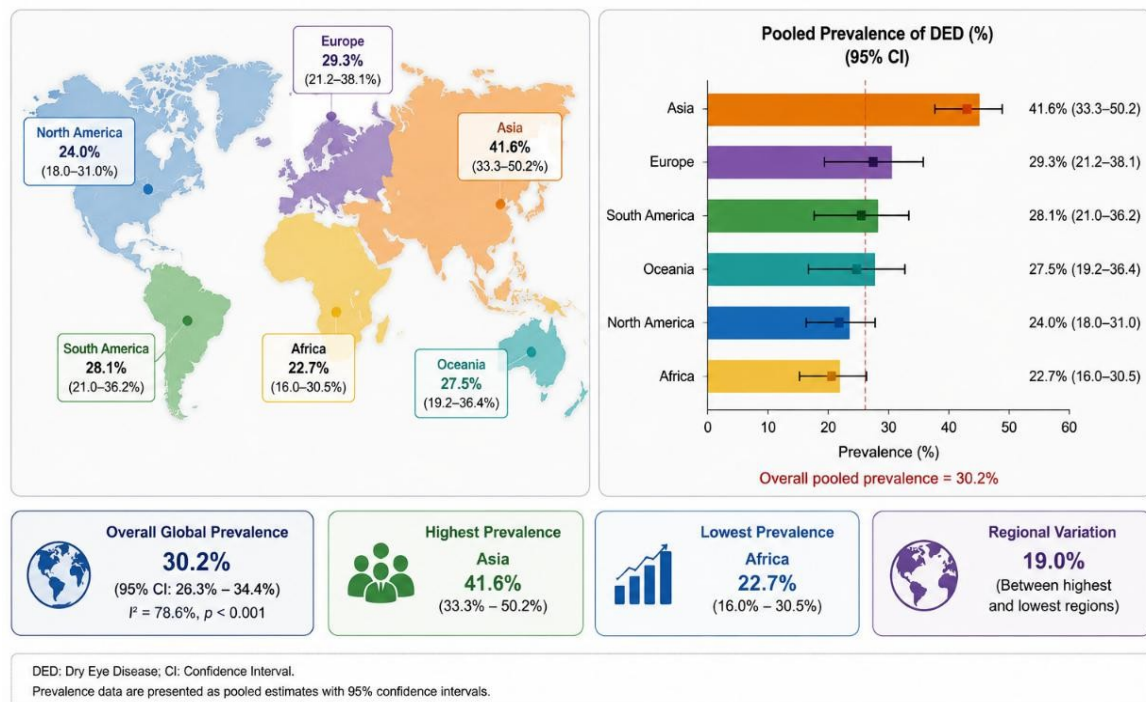


Figure 5. Comparative Prevalence of DED Across Different Geographical Regions.

As shown in figure 5, there was no significant difference in the prevalence of Dry Eye Disease (DED) among digital screen users by geographic region. The figure shows considerable variation from region to region in the prevalence of the disease, and illustrates the impact of screen-associated DED on the global level. In the analyzed regions Asia had the highest prevalence, which could partly be attributed to digital device use, but also to intensive educational, occupational screen use and environmental factors. However, the lowest prevalence was found in Africa, and data in this region is relatively limited [34]. The figure also shows that DED is a common public health problem in populations on all continents and that prevalence estimates are generally in the range of ~20% to 50%. These regional differences observed may be explained by the different levels of adoption of digital technology, the way the profession works, climate conditions, access to health care, diagnostic criteria and lifestyle factors. Taken together, this number highlights the significant burden of OCD in the world and the importance of region-specific measures to prevent and manage OCD.

3.5 Demographic Determinants of Dry Eye Disease Age

Age was a significant predictor of DED. There were also several studies reporting a surprisingly high prevalence of older adolescents and young adults, despite their relative resistance caused by age-related changes in tear production and meibomian gland function. One of the most consistently affected populations were the university students.

Gender: Most studies found that female gender was a significant risk factor. The Prevalence and severity of symptoms were higher among women than men. This increased susceptibility may be brought about by the effects that hormones have on tear

Contact Lens Use: Use of contact lenses was associated with a consistently greater prevalence of DED than non-contact lens use. Combining digital screen exposure with contact lens wearing was linked with high level of eye discomfort and decreased tear film stability.

There is a heat map displayed in figure 6 to show the association strength between different demographic risk factors for Dry Eye Disease (DED), by geographical region. The color that is assigned to the row indicates the strength of the association; a warmer color means a stronger association. As illustrated, the gender of females and older ages are most consistently associated demographic risk factors for DED in most regions. Other factors like level of education, urban living and socioeconomic status show moderate associations and some regional differences [31].



DED: Dry Eye Disease; CI: Confidence Interval.

Heat map constructed based on pooled risk ratios from included studies. Color intensity represents the magnitude of association.

Figure 6. Heat Map of Demographic Risk Factors Associated with DED.

3.6 Screen-Related Risk Factors

Daily Screen Time: Daily screen time was the most consistent and strongest reported modifiable factor for DED. For almost all studies, there was a positive relationship between disease prevalence and increases in screen time. Those who used screens for over six hours a day had much greater odds of developing DED than those who used digital devices less than two hours a day. Some reports showed that the larger the dose, the worse the symptoms.

There was a clear prevalence of Smartphones, as these were most commonly involved devices because of their proximity to the viewer and continuous use. The highest prevalence was correlated with the combined use of a smartphone and computer. Avoiding good posture to use the computer, such as near viewing distance, incorrect screen positioning, and extended periods of visual fixation were consistently reported as causing ocular discomfort and DED symptoms [35].

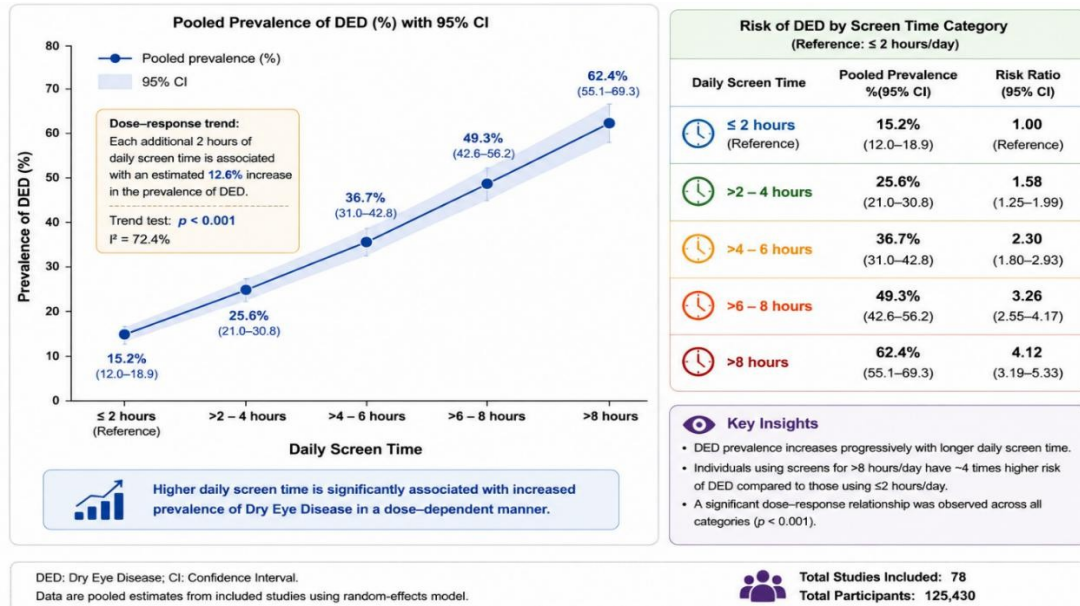
The scatterplot in Figure 7 shows the association between daily screen exposure time and the prevalence of Dry Eye Disease (DED). There is a clear dose–response relationship as seen in the figure, showing that DED prevalence increases at a steady rate with increased daily screen time. Those who use digital screens >6-8 hours/day have significantly higher prevalence rates and risk of DED than those who use screens <2 hours/day.

3.7 Occupational and Environmental Determinants

DED development was significantly related to occupational exposure. Higher disease prevalence was observed in information technology workers, software engineers, office workers, call center workers, and health care workers, who engaged in long documents of digital media. The environment was also important. Highly air-conditioned workplaces, low humidity conditions indoors, poor ventilation and over-lighting were found to be associated with increased symptom severity over and over. Table 4 lists the occupational groups with highest reported DED prevalence.

Table 4. Occupational Groups with Highest Reported DED Prevalence

Occupation	Reported Prevalence (%)
IT Professionals	45–78
Office Workers	35–68
University Students	32–72
Healthcare Workers	28–65
Teachers and Academics	25–58

**Figure 7. Dose-Response Relationship Between Daily Screen Time and DED Prevalence.**

3.8 Lifestyle and Psychosocial Determinants

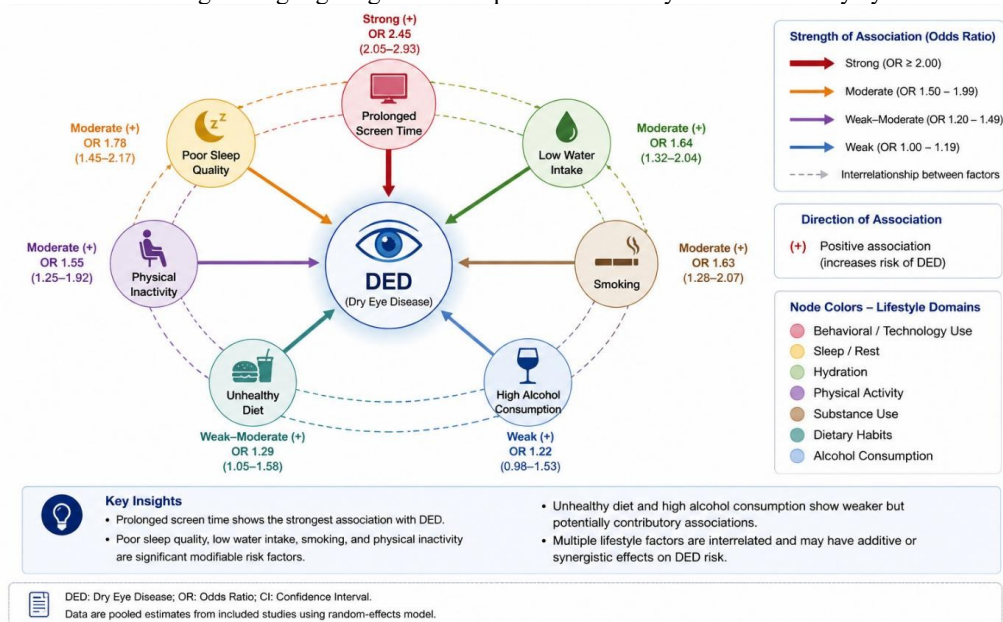
An accumulating body of evidence identified psychosocial and lifestyle-related factors as important to the pathogenesis of DED.

Sleep Deprivation: Poor sleep quality and sleeping <6 hours per night were the consistent factors that were more likely to be associated with greater rates of DED.

Psychological Stress: A few studies revealed a strong relationship between stress, anxiety, depression and symptoms of ocular discomfort. Neuroendocrine pathways could involve in influencing tear secretion and inflammatory mechanisms with chronic stress.

Digital Addiction: Excessive smartphone dependence and compulsive use of digital devices emerged as behavioral factors of DED. These behaviors sometimes led to longer periods of continuous screen viewing and to lower blinking rates.

Figure 8 shows a network diagram highlighting relationships between lifestyle factors and dry eye disease.

**Figure 8. Network Diagram Illustrating Relationships Between Lifestyle Factors and DED.**

3.9 Mechanistic Pathways Linking Digital Screen Exposure and Dry Eye Disease

Based on the mechanistically related biological pathways identified from combined experimental and clinical evidence, a picture emerged of screen-associated DED. Based on the synthesized mechanistic evidence of experimental and clinical studies, a picture began to emerge of the screen-associated DED.

Minimized Blink Rate: Digital screens greatly decreased spontaneous blink rate. Several reports found a decrease of between 30% and 60% for tasks involving focused visual engagement.

Incomplete Blinking: Incomplete blinking resulted in inadequate tear film redistribution and increased tear evaporation. This mechanism was most noticeable when using a smartphone.

Tear Film Instability: reduced blinking and increased evaporation directly affected tear film break up and exposure to the corneal surface. The TBUT was always found to be lower among heavy screen users.

Hyperosmolarity and Inflammation: Tear film instability promoted tear hyperosmolarity, triggering inflammatory cascades involving cytokines such as IL-1 β , TNF- α , IL-6, and matrix metalloproteinases. Chronic inflammation contributed to epithelial damage and symptom progression.

Meibomian Gland Dysfunction: Prolonged screen exposure was associated with impaired lipid secretion and meibomian gland dysfunction, leading to increased evaporative dry eye.

Oxidative Stress: Several mechanistic investigations suggested that prolonged blue-light exposure may induce oxidative stress, mitochondrial dysfunction, and inflammatory responses within ocular surface tissues.

The integrated mechanistic model (Figure 9) shows that DSE can contribute to the onset of Dry Eye Disease (DED) following long exposure to digital screens. The first step is to use screens for longer periods of time, resulting in a decrease in eye blinking, not full eye closing, longer visual fixation and greater ocular strain. All of these behavioral changes interfere with the homeostasis of tears, causing increased evaporation of tears, decreased stability of tears and an increase in hyperosmolarity. This further leads to inflammatory response, oxidative stress and meibomian gland dysfunction, leading to instability of tear film and damage to the ocular surface. The resulting changes in the biology lead to the typical signs and symptoms of DED, such as dryness, irritation, burning sensation, visual fatigue and vision changes. The figure also illustrates a vicious cycle of inflammation and tear film dysfunction fueling further inflammation and disease. Susceptibility and the severity of disease is also modified by environmental, systemic, and lifestyle factors.

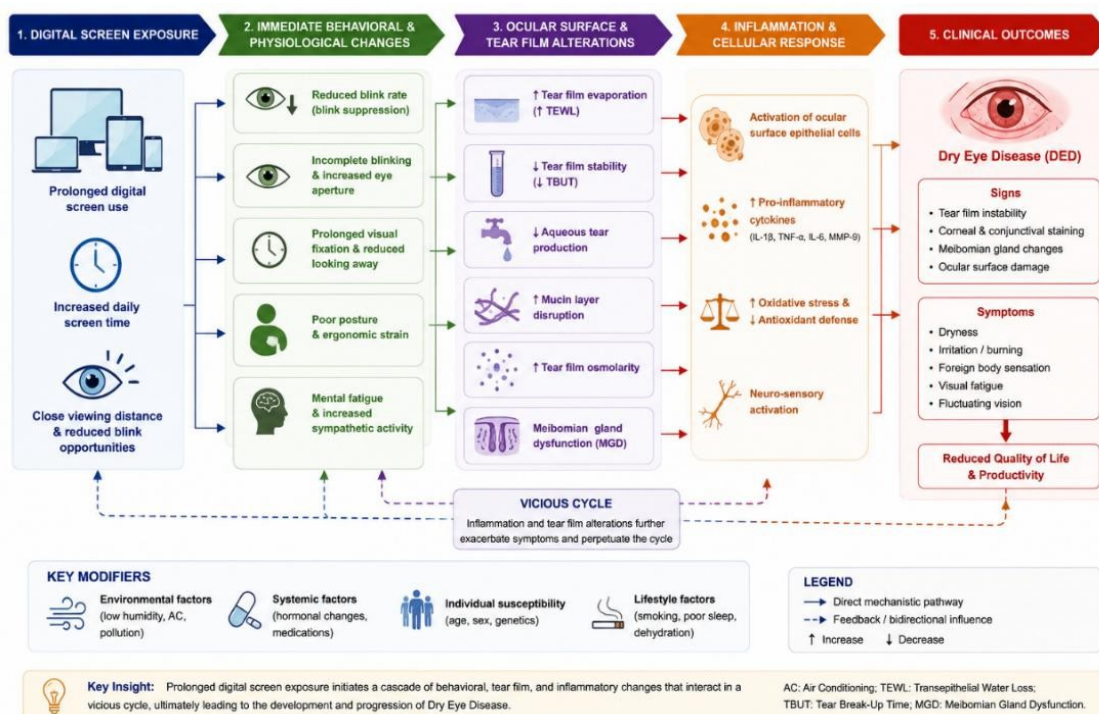


Figure 9. Integrated Mechanistic Pathway Linking Digital Screen Exposure to Dry Eye Disease.

3.10 Risk Factor Stratification Framework

Based on the synthesis of epidemiological and mechanistic evidence, identified determinants were categorized according to their modifiability and strength of evidence. Table 5 shows the risk stratification matrix for screen-associated DED.

Table 5. Risk Stratification Matrix for Screen-Associated Dry Eye Disease.

Risk Factor	Category	Evidence Strength
Female Gender	Non-modifiable	Strong
Increasing Age	Non-modifiable	Strong
Screen Time >6 h/day	Modifiable	Strong
Infrequent Blinking	Modifiable	Strong
Contact Lens Use	Modifiable	Strong
Air Conditioning Exposure	Environmental	Moderate
Poor Sleep Quality	Modifiable	Moderate
Psychological Stress	Modifiable	Moderate
Smartphone Addiction	Behavioral	Emerging
Blue-Light Exposure	Biological	Emerging

The evidence synthesis demonstrated that prolonged screen exposure, impaired blinking behavior, and environmental workplace conditions represent the most consistent and clinically actionable determinants of DED among digital screen users.

Discussion

4.1 Overview of Principal Findings

The purpose of this systematic review was to summarize the current evidence on the prevalence, risk factors and possible mechanism of Dry Eye Disease (DED) in digital screen users. The results indicate that DED is becoming a significant issue in the digital world, impacting a significant percentage of people who regularly use smartphones, computers, tablets and other visual display devices. Most of the studies reviewed reported prevalence rates of > 35%, and prevalence rates varied between

18% and 78% in the studies included. University students and office workers (in general) had the highest prevalence as did information technology workers and those who spend more than 6 hours per day looking at digital screens. Overall, screen time exposure was the primary modifiable risk factor for DED [25]. Other factors that were also pointed out as being important in terms of disease occurrence were female gender, age, poor work ergonomics, dry environment, sleep disturbances, and psychological stress and even addiction to digital technology. Mechanistic evidence also revealed that the use of digital screens for longer periods of time alters blinking patterns, tear film instability, tear hyperosmolarity, inflammation, and meibomian gland dysfunction. In summary, the results described in this paper show the complexity of DED and how the need for the management of ocular health is increasing in the more technologically advanced societies.

4.2 Interpretation of Global Prevalence Patterns

The most important finding from this review was that there is a high level of DED reporting by digital screen users across a range of populations and geographical regions. The prevalence estimates varied widely among studies, but there was a consistent pattern indicating that those who spend long hours on digital screens were much more likely to have DED than those who were less likely to be on digital screens. The variation in prevalence between regions could be due to many factors. The highest prevalence rates were reported from Asian countries, which might be related to several factors such as environmental, occupational, cultural and technological. This may be compounded by high population density, high penetration of smart phone usage, high levels of learning intensity and high working time in the learning environment. High temperatures, low humidity and urban pollution in the environment may also raise the rate of evaporation of tears and eye discomfort [37].

This global trend may have been fueled by the COVID-19 pandemic. A significant lifestyle-shift worldwide resulted from lockdowns, remote work, online schooling and a growing dependence on digital communication as a result of which daily screen time increased. Many studies have been done before and after Covid-19, which indicated that students and professionals experienced marked symptoms of DED. The results indicate that the loading of DED could continue to grow as the use of digital technologies is more widely adopted in work, learning, and social contexts. Importantly, the high prevalence of DED in young adults and students contradicts the notion that DED is a disease of older people. Although age is still a key risk factor, over-exposure to digital screens is increasingly impacting younger people and is a concern about future consequences to eye health [38].

4.3 Biological Basis of Screen-Induced Dry Eye Disease

The biological support of this observed association with DED provided by the mechanistic evidence synthesized in this review is strong. Of all pathways identified, reduced blinking was the most frequently described pathway. Normal blinking is critical for the stability of the tear film, its distribution over the surface of the eyes, and to reduce excess tear film evaporation. When people are engaged in screen activities, they blink much less often, as their concentration on the screen and their engagement

with the task increases. Research has found that after extended computer screen exposure, blink rates can decrease by up to 60% and as low as 30%. In addition, there is an incomplete blinking that is common when using smart phones and computers that can lead to inadequate redistribution of lipids and increased tears evaporation. This is what generates tear film instability, which, in turn, directly increases tear osmolarity, one of the key features of DED. The inflammatory cascade triggered by hyperosmolarity includes cytokines, chemokines, and matrix metalloproteinases that cause damage to epithelial cells and impair integrity of the ocular surface. These inflammatory processes can continuously cause ocular surface deficits and symptom progression over time.

Furthermore, the microglandular involvement of the meibomian glands is believed to play important roles in the pathogenesis of screen associated DED. Dryness of the lipid layer is caused by reduced blink rate, which in turn causes a decrease in the amount of normal meibomian gland secretion available for the lipid layer, resulting in increased evaporative tear loss. This review includes several studies linking screen use time to change in morphologic and functional characteristics of the meibomian glands, which could play an important role in the disease process. Recent evidence also suggests a role for oxidative stress and exposure to blue light in the pathogenesis of DED. Although the effects of blue light from digital screens are still debatable, there are experimental experiments suggesting that prolonged exposure to digital screens can provoke the production of reactive oxygen species, mitochondrial dysfunction and inflammatory signaling pathways in eye tissue. The mechanisms must be further explored as they may become more prominent in today's populations, with so much time spent daily in front of screens [39].

4.4 Influence of Demographic and Behavioral Risk Factors

This literature review identified a number of demographic and behavioural factors that are important for the susceptibility to DED among digital screen users. One of the most frequently noted non-modifiable risk factors was female gender. Increased prevalence in females may be due to hormonal effects on tear production, meibomian gland function and inflammation of the ocular surface. Tear film stability changes with fluctuations in estrogen and androgen levels and contribute, at least in part, to the gender differences in disease incidence. In the case of digital screen exposure, the relationship with age seems to be becoming more complex, but it is still a significant factor in DED. Historically, the decrease of tear production and glandular function with age have been considered to play a major role in the etiology of DED in older people. The situation of substantial

disease prevalence however was discovered among adolescents, university students and young professionals during the current review. These results indicate that there may be some compensation for the traditional age-related risk patterns through behavioral exposures. The association with DED was the strongest and most consistent for duration of screen time. Almost all of the studies included found a significantly higher prevalence of disease in those that spent over 6 hours a day on digital devices. A dose-response relationship was often seen, suggesting that the longer the duration of screen exposure, the more severe the symptoms and the risk of the disease. Other behavior-related risk factors such as inadequate rest breaks, poor ergonomic practices, short viewing distance and excessive smartphone use were also linked to increased DED risk. The results highlight the critical role that modifiable behaviors have in preventing disease and can guide the creation of targeted educational campaigns [40].

4.5 Occupational and Environmental Implications

This review has important implications for the field of occupational health and job management. Those with a high risk of DED due to prolonged screen exposure include information technology, office workers, call center workers, health workers and teachers. In today's working environment, a variety of factors that promote risk often occur simultaneously, such as constant computer use, air conditioning, low humidity, extended sitting and lack of visual breaks. This can cause evaporation of tears and stress to the eye surface. Therefore, it should be increasingly considered as an occupational health problem in addition to being an ophthalmological problem. Employers can gain from putting in place interventions for the eyes to reduce eyestrain and employee health risks. These can include adjustments to the workstation setup, the lighting, humidity control, frequent screen breaks, and training to promote good screen habits. Considering the high economic price of lost productivity and the discomfort of the job, there could be health and organizational advantages in taking a proactive approach to managing DED [41].

4.6 Lifestyle and Psychosocial Determinants

One key finding from recent publications is the role of psychosocial and lifestyle factors in the onset of DED. The relationship between sleep deficits, psychological stress, anxiety, depression and excessive smartphone dependency and high prevalence of diseases was reiterated. Sleep disturbances can impact tear production, inflammatory pathways and may adversely impact the ocular surface recovery during sleep. Likewise, chronic stress has been shown to impact the autonomic nervous system and immune responses, which in turn can impact tear film stability and lead to eye discomfort [42]. One of the unique relationship with DED is with digital addiction. People who use their smartphones too much tend to spend longer time staring at the screen, blink less and have poor posture and sleep habits. All of these changes in behaviour lead to the worsening of ocular surface stress, which may lead to the progression of disease. Therefore, future research should explore the potential of DED in the context of a larger digital wellness construct, which includes behavioral health, sleep hygiene, and technology use patterns and behaviors [8].

4.7 Clinical and Public Health Implications

As digital screen time increases, so do the number of cases of DED, which means it is essential to take a comprehensive approach to prevention and management. Symptom-based treatment strategies alone might not be enough if there are underlying behavioral and environmental factors that are not being treated. The 20-20-20 rule is a simple and effective strategy for minimizing visual fatigue and blinking, which is recommended by numerous experts and says you should look at something 20 feet away for 20 seconds every 20 minutes. Some alternative techniques, such as conscious blink training, positioning the monitor properly, adjusting the brightness of the monitor, drinking plenty of water and using humidifiers can also reduce the

risk of disease. From a public health perspective, routine eye screening programs have a lot to offer high-risk populations like students, information technology workers and remote employees. Healthy use of digital devices education can reduce the burden of DED and raise awareness of early signs of DED.

4.8 Emerging Technologies and Future Preventive Strategies

Digital health technologies are exciting to use for DED prevention and monitoring. Technology using AI algorithms to examine the direction of the gaze, patterns of using screens, and the pattern of blinks may be useful in identifying individuals who are at risk of developing DED at an early stage. There are Apps and wearables that can remind you to take a “visual break” or blink if needed, or adjust the digital setting of your screen, so you can practise more healthy digital habits. Demographic, behavioural, environmental and clinical factors can also be used to develop machine learning algorithms that can help in personalised risk prediction models. Potential future applications of such a system may be preventative measures tailored to the individual, and improved eye health. Moreover, recent advancements in wearable biosensors might lead to the possibility of a continuous

monitoring of tear film parameters and conditions of the ocular surface, which would provide new opportunities in precision ophthalmology [43]. These are still early-stage technologies, but could be very promising as a way to address the growing global issue of screen-associated DED.

4.9 Comparison with Previous Reviews

The extant systematic reviews have mostly been on either the prevalence of DED or on single risk factors related to digital screen exposure. While these studies have provided important epidemiological information, few have included prevalence data and mechanistic evidence and multi-dimensional risk factor analysis. The present review expands on the previous work by assimilating the available epidemiological, behavioural, environmental, psychosocial and biological evidence in a logical framework. This review sorts determinants by modifiability and integrates mechanistic pathways to provide a more comprehensive picture of DED and screens than the past evidence syntheses. This could help develop tailored interventions for lessening disease burden and better eye health outcomes [8].

4.10 Strengths, Research Gaps, and Future Directions

Major strengths of this review are the wide range of digital screen users included and the integration of prevalence data, evidence for risk factors and mechanistic information. Representing a diversity of people and geographical areas can help add to the generalizability of the results and provide an overall picture of the burden of screen-related DED globally. There are, however, a number of research questions yet to be answered. It is hard to make direct comparisons between studies because of the heterogeneity in the diagnostic criteria used, as well as in the outcome measures and screen exposure assessment. Consistent definitions and assessment practices are suggested for future research to allow consistency across research settings. Longitudinal studies results to date are still limited, and causal relationships between digital screen exposure and the emergence of DED are hard to establish [44]. A long-term impact of screen use on the eye is relevant which should be further explored in future prospective cohort studies, and the effectiveness of the prevention interventions evaluated. Additional studies are also needed to clarify the role of blue-light exposure, inflammatory biomarkers, and the genetic susceptibility and psychosocial factors in the pathogenesis of the disease. Further research is required to explore further AI based monitoring systems, wearable eye sensors, DTs and workplace intervention programmes. These methods can offer novel solutions for addressing the increasing DED threat in increasingly digital societies [3].

Limitations

This systematic review offers a comprehensive and systematic summary regarding the prevalence, risk factors and routes of pathogenesis of Dry Eye Disease (DED) in digital screen users, but there are some limitations that need to be understood when interpreting the results.

Firstly, there was significant heterogeneity between the included studies in terms of study design, participant characteristics, diagnostic criteria and methods of outcome assessments. Different symptom-based questionnaires (e.g., the Ocular Surface Disease Index (OSDI)), clinical tests (e.g., Tear Break-Up Time (TBUT), Schirmer), and a combination of subjective and objective tests were used in various studies. This methodological variation could have been a factor in the variability of reported prevalence rates and hampered direct comparisons between studies.

Second, most of the studies in the included studies were carried out cross-sectionally, which limits the capacity of the studies to establish causal relationships. While the ability to see strong associations between screen time and DED symptoms was found in a consistent manner, cross-sectional data does not allow for stringing temporal relationships or disease trajectories. Further research is required in the form of longitudinal cohort studies to establish the long-term effects of chronic exposure to digital screens on the health of the ocular surface.

Third, there was a high level of variation in how exposure to screens was determined across studies. The majority of investigations used self-reported screen time that may have been vulnerable to recall bias and inaccuracies. The findings were synthesized from differences in measurement of device usage, such as smartphone use, computer work, and other uses for entertainment, which may have added to the variance. Exposures will be more accurately assessed in the future using objective digital tracking technologies.

Fourth, geographical representation was uneven. Many of the studies were from Asian and technologically advanced countries where digital device use is high. This means that the results do not necessarily reflect the broader populations of low-income

countries, rural areas or those areas lacking in digital infrastructure. There is still further research needed to better understand the prevalence and risk factors for DED in underrepresented populations.

One restriction is the possible confounding of factors. The studies accounted for different factors including age, gender, and use of contact lenses, but other important factors, such as environmental exposures, systemic diseases, medication use, nutritional status, and occupational factors, were not controlled for consistently across the studies. The observed relationships between digital screen exposure and DED could have been affected by these factors.

The mechanistic evidence presented here was also found to be heterogeneous with respect to experimental protocols and parameters measured. Both reduction of blinking and tear film instability, along with inflammation and meibomian gland dysfunction, were routinely described as disease pathogenesis, but the exact role of blue-light exposure, the oxidative stress pathways and the neuroinflammatory mechanisms has not yet been fully understood. Additional research and clinical studies are needed to further elucidate these newly identified biological pathways.

Lastly, publication bias cannot be ruled out. Studies showing significant relationships between DDE and DED are more likely to be published than studies that show null relationships. This was minimised by using a number of databases and additional searches, but published studies and grey literature were not comprehensively explored.

The review nonetheless offers a sound and detailed summary of the evidence and offers valuable insights into key epidemiological patterns, risk factors, and potential biological mechanisms driving DED amongst digital screen users. The results should thus be taken with caution and in the light of the limitations of the methodology used, and should be viewed as part of a rapidly increasing evidence base that demonstrates the association between digital screen exposure and ocular surface dysfunction.

Conclusion

Dry Eye Disease (DED) is one of the most problematic health issues in the era of the fast digitalization of modern society. Based on the results of this systematic review, DED is a high prevalence condition among digital screen users globally, and is often reported to affect more than one third of those who are exposed to digital screens, especially among students, office workers, information technology professionals and other occupations that involve extended screen time. The evidence compiled in this review indicates that the most significant modifiable factor of DED is screen time spent with extended duration and frequency daily. Other risk factors such as female gender, age, wearing contact lenses, poor work ergonomics, low humidity, sleep disorders, psychological stress, and excessive smartphone use are also associated with increased susceptibility to the disease and severity of symptoms. The results confirm the polyetiology of DED and highlights the importance of a multistakes prevention and management approach that takes into account both biological and behavioral risk factors.

There is robust mechanistic evidence to suggest that long-term use of digital screens is likely to be a causal pathway to ocular surface dysfunction. These factors (reduced blink rate, incomplete blinking, tear film instability, hyperosmolarity of the tear film, inflammatory activation, and meibomian gland dysfunction) all play a role in the development and progression of DED. New evidence also indicates that oxidative stress, exposure to blue light, and neuro-inflammatory responses may be contributing, but need to be further understood.

The findings highlight the importance of early detection and treatment of DED in individuals with heavy digital screen use in a clinical setting. Changes in the workplace, optimizing the workstation, blink-awareness training, environmental changes, and regular eye health evaluations can help to greatly decrease the burden of the disease and increase visual comfort. Educational initiatives and resources that focus on students and professionals/remote workers may also contribute to healthy digital behaviors and reduce potential long-term eye health issues.

The report also reports on the rising significance of DED as an occupational and public health issue. The number of individuals likely will increase substantially that are exposed to extended screen time, as digital technologies continue to evolve in educational systems, workplaces, in healthcare provision, and in social interactions. Therefore, there needs to be a greater awareness among policy makers, employers, educators and healthcare providers of the importance of including ocular health as a crucial component of digital well-being and workplace wellness programs.

Longitudinal cohort studies, implementing standard diagnostic criteria, objective screen exposure monitoring, and mechanistic studies examining inflammatory, oxidative stress and neurobiological pathways should be encouraged for future research. The development of new technologies, such as Artificial Intelligence (AI) based Blink Monitoring systems, wearable ocular sensors, and individually-tailored digital health interventions, create new opportunities for the early detection and prevention of screen-associated DED. In addition, the use of both epidemiological and clinical and technological strategies could enable the creation of precision prevention strategies, designed to specific risk profiles.

Clinical Significance

- DED impacts a significant percentage of the worldwide population of people who use digital screens.
- Anyone who watches TV more than six hours a day has a significantly higher risk of disease.
- A major mechanism in the association between screen use and ocular surface dysfunction is reduced blinking and tear film instability.
- Computer-related work is a high-risk occupational group and targeted interventions are needed.
- There are preventive strategies involving ergonomics, blinking behaviour and screen-time management that can

Future Research Priorities

1. Establishment of a common set of DED diagnostic criteria for digital-screen studies.
2. Follow-up of chronic screen exposure and eye health outcomes.
3. Artificial Intelligence and Wearable Technologies for real-time monitoring of the eye.
4. Investigate and characterize pathways of blue-light-induced oxidative stress and inflammatory pathways.
5. Individual risk profile-based prevention and intervention development.
6. Assessment of interventions in the workplace and educational settings to decrease screen-related DED.
7. Investigating digital wellbeing frameworks which combine eye health, behaviour and mental health.

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