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Review

White Paper on Dry Eye-Friendly Technologies for Lighting Health

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ABSTRACT

Dry eye syndrome (DES) is a multifactorial chronic ocular surface disorder caused by tear film instability, ocular surface inflammation, and neural abnormalities. With the widespread adoption of LED lighting, high-energy blue light (400-450 nm), flicker effects, and improper color temperature have emerged as new risk factors, disrupting tear film stability and inducing oxidative stress. Epidemiological studies indicate higher prevalence rates among the elderly, women, and populations in arid regions. Healthy lighting strategies emphasize spectral optimization, flicker reduction, and dynamic adjustment of brightness and color temperature, utilizing technologies such as full-spectrum LEDs and high-frequency PWM dimming. Future efforts require interdisciplinary collaboration to establish industry standards, develop smart lighting systems, and enhance public education to mitigate the socioeconomic burden of DES.

1. INTRODUCTION

1.1 Definition and Background of Dry Eye

Dry eye (Dry Eye) is a chronic ocular surface disease caused by multiple factors, characterized by abnormalities in the quality, quantity, and dynamics of tears, leading to tear film instability or imbalance in the ocular surface microenvironment. It may be accompanied by increased tear osmolarity, ocular surface inflammatory reactions, tissue damage, and neural abnormalities, resulting in various ocular discomfort symptoms and/or visual dysfunction [1]. Dry eye is a common ophthalmic disorder, with a global prevalence ranging from 26% to 70% [2].

The etiological origins of dry eye vary, with inflammation playing a critical role in its pathogenesis. Additionally, apoptosis, neural regulation [3], and sex hormones collectively contribute to the disease process. Risk factors for dry eye include age, female sex, systemic diseases (particularly immune and endocrine disorders), unhealthy lifestyle habits (e.g., improper lighting, prolonged screen time, insufficient outdoor activities, and contact lens wear), environmental conditions (such as air pollution, low humidity, and strong winds), as well as the use of topical or systemic medications (e.g., antidepressants and antihistamines).

In recent years, with the rapid advancement of lighting technology, light-emitting diodes (LEDs) have been widely adopted as a novel light source in illumination, display, and related photonic product applications. This has contributed to a year-by-year increase in dry eye cases, making "healthy lighting or light health" a crucial direction for industrial development. The impact of lighting on ocular health has become a major societal concern and a hot topic of public interest.

1.2 The Impact of Lighting on Dry Eye

In recent years, with the continuous evolution of lighting technology, illumination devices have transitioned from traditional incandescent lamps to modern LED lighting and smart lighting systems. The ongoing advancements in lighting technology have not only enhanced luminous efficiency but also improved light quality, laying a technical foundation for healthy lighting. However, due to insufficient public awareness of the hazards posed by poor lighting environments, neglect in selecting and optimizing lighting conditions, and the tendency of economically disadvantaged populations to opt for low-cost but inferior-quality lighting products, the risk of dry eye syndrome has increased.

Lighting spectra can provide a spectral distribution similar to natural light, encompassing the entire visible spectrum. High-energy blue light (wavelength 400–450 nm) irradiating corneal epithelial cells can activate stress response signaling pathways, leading to an imbalance between the oxidative and antioxidant systems in the body. This results in excessive production of reactive oxygen species, disrupting the ocular surface microenvironment [4] and inducing ocular surface inflammation, thereby contributing to dry eye. High-color-temperature (>5300 K) light sources contain a higher proportion of blue light, which not only damages ocular surface structures and reduces tear film breakup time but also suppresses melatonin secretion. Melatonin possesses potent antioxidant properties [5] and can indirectly alleviate dry eye-related ocular surface inflammation. Therefore, exposure to high-color-temperature lighting can exacerbate dry eye symptoms.

Low-frequency flickering in lighting devices can interfere with normal blink frequency, leading to a reduction in blink rate. Decreased blink frequency not only increases ocular surface exposure and slows tear film renewal but also impairs meibomian gland secretion and natural lipid excretion. This results in uneven distribution of the tear film's outermost lipid layer, accelerating aqueous tear evaporation (shortening tear film breakup time by ≥30%). Excessive tear evaporation elevates tear osmolarity and leads to the accumulation of inflammatory factors on the ocular surface, damaging corneal epithelial cells, conjunctival epithelial cells, and conjunctival goblet cells. Consequently, ocular surface epithelial injury occurs, accompanied by symptoms such as dryness, pain, and foreign body sensation. The instability of tear film homeostasis and microenvironmental imbalance further exacerbate tear hyperosmolarity, aggravating dry eye and creating a vicious cycle.

2. CURRENT STATUS OF DRY EYE

2.1 Epidemiological Data of Dry Eye

Globally, the prevalence of dry eye ranges from 5% to 50%, significantly impairing patients' quality of life, work productivity, and mental health, while also imposing a substantial socioeconomic burden [6]. The considerable variation in reported prevalence rates may be attributed to differences in diagnostic criteria, as well as the characteristics and etiological factors of the surveyed populations.Studies indicate that the prevalence of dry eye among elderly populations aged 60 and above in China is relatively high, approximately 34.4% [7]. In arid climate regions such as the Middle East, the prevalence reaches 32.1% [8]. Additionally, women exhibit a higher prevalence (48.2%) compared to men (33.5%), suggesting that age, environmental conditions, and sex [9] are significant risk factors for dry eye.Other contributing factors include meibomian gland dysfunction, prolonged contact lens wear, excessive use of digital devices (e.g., smartphones and computers), poor lighting conditions, and inadequate sleep quality. These factors collectively exacerbate the risk and severity of dry eye syndrome.

2.2 Major Risk Factors for Dry Eye

① Systemic Diseases: Particularly immune system disorders and endocrine imbalances, such as Sjögren's syndrome, Stevens-Johnson syndrome[10], graft-versus-host disease, various connective tissue and collagen vascular diseases, severe liver dysfunction, thyroid disorders, diabetes, gout, postmenopausal hormonal changes, vitamin A deficiency, and androgen deficiency. ② Ocular Local Factors:a) Local infections and immune-related conditions: Infectious conjunctivitis, allergic conjunctivitis, abnormal subbasal corneal nerve plexus density, dysfunction of the lacrimal gland, meibomian glands, ocular surface epithelial cells (e.g., goblet cells), and corneal nerves, as well as Demodex blepharitis. b) Abnormalities in tear dynamics: Conditions such as floppy eyelid syndrome, conjunctivochalasis, caruncle hypertrophy, blepharospasm, and ocular rosacea. ③ Environmental Factors Including air pollution, light pollution, radiation exposure, high altitude, low humidity, and strong winds. ④ Lifestyle-Related Factors[11] Prolonged digital screen use, insufficient outdoor activity, extended near-work tasks, sleep deprivation, air conditioning use, smoking, long-term contact lens wear, eye makeup, and prolonged driving. ⑤ Surgery-Related Factors[12] Postoperative damage or loss of the lacrimal gland, accessory lacrimal glands, meibomian glands, ocular surface epithelium, or subbasal corneal nerve plexus. Surgical alterations in ocular surface smoothness or curvature, lacrimal duct dilation, abnormal punctum position, or eyelid margin defects may also contribute. ⑥ Medication-Related Factors[13] a) Systemic medications: Hormone replacement therapy (e.g., postmenopausal estrogen), antidepressant, antihistamines,anticholinergics, isotretinoin, diuretics, oral contraceptives, and chemotherapy drugs. b) Topical medications: Ocular disinfectants, antiviral drugs, antiglaucoma medications (e.g., beta-blockers), and preservative-containing eye drops or ointments. ⑦ Other Factors Psychological conditions such as anxiety and depression, which may exacerbate dry eye symptoms.

2.3 Correlation Analysis Between Lighting Product Usage and Dry Eye Epidemiology

The advancement of science and technology has led to the emergence of numerous promising new lighting technologies. Modern lighting technologies provide an efficient, long-lasting, and customizable technical foundation for healthy illumination [14]. The core concept of healthy lighting lies in promoting both physiological and psychological well-being through scientifically optimized light exposure. Inappropriate lighting environments may not only reduce visual comfort and induce eye strain, but could also potentially cause irreversible ocular damage.

For instance, with the widespread adoption of light-emitting diode (LED) technology - valued for its energy efficiency, environmental friendliness, and adjustable brightness/spectrum characteristics - LEDs have become the current mainstream light source. However, LED lighting presents several significant health and safety concerns. Due to its small emission area and high luminance characteristics, LED sources are prone to produce glare. Furthermore, their relatively high blue light component may lead to blue light hazard, potentially contributing to conditions such as dry eye syndrome.

2.4 Common Lighting Usage Behaviors Among Dry Eye Patients

In our routine work, we employed multiple methodologies including in-depth user interviews, questionnaire surveys, and systematic analysis of user-generated content on social media platforms to comprehensively understand users' visual experiences when using smart terminal lighting products. Our findings revealed that prior to the onset of dry eye symptoms, users frequently worked or studied in environments with insufficient illumination, requiring their eyes to exert greater effort for focus maintenance, which may lead to reduced blink rates.

Additionally, dry eye patients tend to frequently adjust the screen brightness of electronic devices such as smartphones and computers. Research indicates that intense light exposure can induce pupillary constriction, resulting in sustained tension of the orbicularis oculi muscle and accelerated tear evaporation. Conversely, low brightness conditions force excessive contraction of the ciliary muscle to enhance light signal capture, thereby inducing visual fatigue.

3. INDUSTRY STANDARDS AND BEST PRACTICES

3.1 Expert Consensus and Academic Review: Current Research on the Association Between Healthy Lighting and Dry Eye

The 2024 edition of the Chinese Expert Consensus on Clinical Diagnosis and Treatment of Dry Eye highlights that the onset of dry eye is closely associated with lifestyle factors, including sleep disorders [15] and prolonged use of video display terminals (VDTs). Excessive screen brightness (illumination intensity) and blue light radiation from VDTs have been shown to exacerbate dry eye symptoms, underscoring the importance of healthy lighting for ocular health. Furthermore, other lighting characteristics such as spectral properties, color temperature, luminous intensity, illumination uniformity, and flicker all contribute to the development and progression of dry eye.

3.1.1 Research Advances in Pathogenesis

(1) Reduced Blink Rate: Lighting color temperature may influence blink frequency. Under cool-toned lighting, individuals tend to blink less frequently, leading to decreased tear secretion and aggravated dry eye symptoms.

(2) Environmental Factors: Low humidity and warm air circulation in air-conditioned environments accelerate tear evaporation, resulting in ocular surface dryness and discomfort [16].

4. DESIGN AND CALIBRATION OF HEAITHY DEVICES

4.1 Functional Recommendations for Smart Devices Targeting Dry Eye Users

4.1.1 Current Analysis of Eye Protection Technologies in Smart Devices

Contemporary lighting devices present multiple challenges to ocular health through their brightness, color temperature, color rendering, and flicker characteristics. For instance, prolonged exposure to excessively bright environments may lead to unconscious reduction in blink rate. Blinking serves as a crucial mechanism for maintaining ocular moisture by facilitating even distribution of tears across the ocular surface. Reduced blink frequency accelerates tear evaporation, thereby inducing dry eye symptoms. Additionally, high color temperature lighting contains elevated blue light components, which decrease corneal epithelial cell viability and contribute to chronic ocular surface inflammation.

Fortunately, many lighting manufacturers have begun prioritizing consumers' ocular health concerns. Recent years have witnessed the emergence of numerous innovative eye protection technologies, offering comprehensive hardware and software solutions to safeguard users' visual health.

At the hardware level, technological innovations can be primarily categorized into four directions: optical structure optimization, spectral control, dimming technology innovation, and natural light simulation.The honeycomb grid (Cell Louver) effectively reduces direct glare and reflected glare through its cellular structure that blocks direct light, redistributes light, and controls light distribution, thereby improving visual comfort. Fresnel lenses reduce lens thickness and weight while maintaining optical performance by dividing the lens surface into a series of concentric rings, used to control light propagation and reduce glare. Reflectors prevent glare generation by controlling, guiding, and blocking light, as well as optimizing light distribution curves and using anti-glare materials. Reflectors can be used in combination with lenses to further control and optimize light propagation. Lenses can assist reflectors in more precisely directing light to target areas, reducing glare.The International Commission on Illumination (CIE) provides application guidelines for LED lighting products in indoor work environments in its "Application Guide for LED Lighting Products for Indoor Work". The guidelines specify that LED lighting products should comply with the IEC 62471 photobiological safety standard, particularly regarding blue light hazard. It is recommended to prioritize low blue light risk options: RG0 (no risk) or RG1 (low risk).PWM (Pulse Width Modulation) dimming improvements reduce perceived flicker by increasing PWM frequency beyond the human eye's detectable range, thereby eliminating the need for frequent pupil diameter adjustments and reducing the workload on iris muscles. DC dimming (analog dimming) adjusts brightness by changing the current flowing through LEDs, fundamentally avoiding the flicker issues associated with PWM dimming. However, DC dimming may affect LED color reproduction and lifespan. Additionally, PWM dimming and DC dimming can be combined, using different dimming methods in different brightness ranges to achieve flicker-free operation and good color performance.Full-spectrum LED technology improves LED packaging materials and phosphor formulations to enable LED emitted light to cover a broader wavelength range from ultraviolet to infrared, more closely approximating the continuous spectrum of natural light. Dynamic spectrum adjustment technology integrates multiple LED light sources with different spectra in luminaires and uses intelligent control systems to dynamically adjust the brightness ratio of each light source according to time, environment, and user needs, thereby simulating the dynamic changes of natural light spectrum. These technologies can provide more balanced light, reduce blue light hazard, and enhance red light components, benefiting human health and visual comfort.

At the software level, eye protection is achieved through four approaches: spectrum management, brightness adjustment, color management, and behavioral intervention. Eye protection mode reduces the intensity of blue light peaks in the 415-455nm wavelength band to decrease harmful blue light exposure. Similarly, sleep aid mode reduces blue light around 480nm wavelength to lower melatonin suppression risk. Circadian rhythm dimming is a technology that adjusts lighting brightness and color temperature according to the human body's natural biological clock (circadian rhythm). This dimming method aims to simulate natural light changes, where lighting equipment can adjust brightness based on time or external light sensors to mimic natural light variations. Circadian rhythm dimming also involves color temperature adjustment. Morning and evening sunlight has lower color temperature (warmer, approximately 2700K-3000K), while midday sunlight has higher color temperature (cooler, approximately 5000K-6500K). Lighting equipment can simulate these changes, providing warmer light in the morning, gradually transitioning to cooler light during the day, and returning to warmer light in the evening. Eye-tracking sensors can capture user posture, viewing distance, blink frequency, tear film breakup time (TFBUT), etc. Distance reminders trigger warnings when detecting users' viewing distance is too close, and the warning continues until the user reaches their set safe viewing distance. Smart lighting equipment has blink guidance functionality that can trigger corresponding alerts to remind users to blink when detecting that the user's blink frequency per minute falls below a certain threshold.

4.1.2 Functional Recommendations for Dry Eye-Friendly Smart Devices

Based on epidemiological characteristics of dry eye syndrome and the summarized mainstream eye-protection technologies in lighting devices, we propose the following recommendations for establishing an ocular health protection system in dry eye-friendly lighting equipment:

Reduction of Harmful Blue Light Component

Full-spectrum light sources can provide spectral distributions similar to natural light, containing all visible wavelength components to create a more natural and comfortable lighting environment. However, LEDs emit substantial amounts of blue light (400-500nm wavelength), which possesses the highest energy in the visible spectrum. Ocular exposure to blue light has been closely associated with the pathogenesis and progression of various ophthalmic conditions including dry eye syndrome, cataracts, age-related macular degeneration, and retinal pigment degeneration [17]. Blue light irradiation activates stress response signaling pathways in corneal epithelial cells. The ROS-activated P38MAPK pathway alters mitochondrial membrane potential, disrupting the balance between oxidative and antioxidant systems, leading to excessive production of free oxidative products that damage the internal environment. Post-irradiation generation of hydroxyl radicals and superoxide anions can induce corneal epithelial cell damage, ultimately resulting in apoptosis and dry eye development. Furthermore, blue light penetrating the cornea and lens not only reduces subjective and objective sleepiness, prolongs sleep onset latency, and decreases REM and slow-wave sleep, but also stimulates the brain to inhibit melatonin secretion while promoting adrenocorticotropic hormone release, thereby disrupting hormonal balance and directly affecting sleep quality [18]. Concurrently, studies demonstrate that sleep deprivation suppresses PPAR α function, leading to microvilli abnormalities, impaired tear film adhesion through reduced fatty acid availability, and decreased TRPV6 expression with Ezrin phosphorylation, ultimately contributing to dry eye syndrome [19].

Mitigation of Color Temperature Hazards

Color temperature, measured in Kelvin (K), represents the ratio of red to blue light components in a light source's spectrum. Low color temperature (<3300K) emits yellowish-red light that induces warmth and relaxation, while high color temperature (>5300K) produces bluish-white light that promotes alertness and concentration. During daytime, higher color temperatures help prevent excessive cone cell regulation stress;

nighttime maintenance of lower color temperatures reduces melatonin suppression from harmful blue light, thereby improving sleep quality and indirectly alleviating ocular surface inflammation associated with dry eye. Lighting color temperature may influence blink frequency, where cool-toned illumination potentially induces subconscious blink reduction, decreasing tear secretion and exacerbating dry eye symptoms. Healthy lighting should employ appropriate color temperatures according to different scenarios and times - higher color temperatures during mornings/daytime to enhance alertness and work efficiency, and lower color temperatures in evenings to facilitate melatonin secretion and sleep induction [20].

Reduction of Brightness-Related Hazards

Prolonged exposure to high-brightness screens (computers, smartphones, or televisions) may induce eye strain and dry eye symptoms. Excessive screen brightness causes sustained tension in palpebral muscles, which not only increases radial pressure on glandular ducts leading to luminal narrowing, but also elevates incomplete blink probability, resulting in reduced tear meniscus height and shortened tear film breakup time. Conversely, working or studying in underlit environments forces excessive ocular accommodation, potentially causing eye fatigue and dry eye. Additionally, insufficient illumination may prolong ocular tension states, further aggravating dry eye symptoms.

Minimization of Flicker Hazards

Flicker refers to rapid luminance fluctuations perceptible as visual flickering, attributable to various factors including power frequency and lighting design defects. Flickering light sources may induce persistent accommodative adjustments, leading to visual fatigue - a common dry eye symptom that may exacerbate the condition when prolonged. Flicker effects can disrupt normal blink frequency, and since blinking constitutes a crucial mechanism for ocular surface lubrication, reduced blink rates may impair tear secretion and distribution, worsening dry eye. Furthermore, flickering illumination may cause periocular muscle tension, potentially compromising local circulation and tear production. To mitigate flicker-induced dry eye aggravation, flicker-free or low-flicker lighting devices should be selected, such as LED lamps or high-frequency PWM-tuned OLED displays (IEEE Std 1789-2015 specifies >1250Hz as low health risk and >3125Hz as risk-free ranges).

Dynamic Intelligent Adjustment Capability in Accordance with User Environment

The intelligent regulation of a healthy lighting system can be integrated with sensors to automatically adjust lighting parameters based on factors such as ambient light, time of day, and human activity. This enables more precise circadian rhythm dimming, ensuring that indoor light is in harmony with outdoor light. Photocells can detect the intensity of surrounding light and automatically adjust the brightness of luminaires according to preset logic. For example, during the day when there is ample light, the luminaires will automatically dim or turn off; at night or in low-light conditions, the luminaires will automatically brighten. Users can also preset different lighting scenes through scene control, such as “movie mode,” “reading mode,” and “party mode,” with each scene corresponding to different combinations of luminaire brightness and color. By simply pressing a button, the desired lighting effect for different scenes can be achieved. The system can also automatically adjust the color temperature of luminaires based on ambient temperature. For instance, warm yellow light can be used in cold winter, while cool blue light can be employed in hot summer. The dynamic intelligent adjustment capability of lighting equipment is continuously evolving and will become more intelligent, personalized, and user-friendly in the future. These capabilities can not only enhance the energy efficiency and user experience of lighting systems but also bring more convenience and comfort to our lives.

4.2 Design Principles for Users with Dry Eyes

4.2.1 Examples of Technical Directions and Adjustment Guidance

Effective spectral management can reduce eye fatigue, thereby lowering the probability of dry eye occurrence. The eye-protection mode of lighting devices reduces eye fatigue and dry eye symptoms by decreasing the amount of blue light in the light source. Reducing the energy of blue light can mitigate the stimulation to the eyes, alleviating dryness and fatigue. Intelligent color temperature adjustment is another effective attempt at spectral management. When ambient light changes, intelligent color temperature adjustment can automatically modify the color temperature of the light source to better coordinate with the surrounding environment. High-frequency PWM dimming achieves a dimming effect by rapidly switching the brightness of the light source, reducing the eye's regulatory burden under different lighting conditions, decreasing glare, and lowering visual fatigue, thereby effectively reducing the incidence of dry eye. With the development of material science and nanotechnology, the performance and application scope of anti-glare coatings are continuously expanding. Diffuse reflection coatings reduce glare by causing light to scatter on the surface instead of forming mirror-like reflections. These coatings are typically used in situations where extensive uniform lighting is required, such as certain types of displays and lighting devices. There are many other technical directions for effectively alleviating dry eye, some of which are still under research and exploration. Scholars and experts are welcome to join in the exploration of technical directions for improving visual comfort and alleviating dry eye.

4.2.2 Examples of Human-Computer Interaction

At present, many lighting manufacturers have developed intelligent reminder systems. Users can receive real-time dynamic prompts on their mobile phones when they are too close to their screens or when their blinking frequency decreases, allowing them to promptly change their behavior. The blink frequency monitoring module in the "dry eye-friendly" function of lighting products can monitor users' blink frequency in real-time. When users become so engrossed that they forget to blink, the "dry eye-friendly" function can timely remind them to blink, promoting tear secretion and preventing and alleviating the occurrence of dry eye.

4.3 Lighting Calibration Suggestions for Users with Dry Eyes

If you are concerned about your eye health or have already experienced symptoms of dry eye, you can adjust your lighting settings according to the following suggestions. For severe dry eye users, an intelligent lighting system can be chosen. The intelligent lighting system [21] can be linked with devices such as computers and tablets to automatically adjust indoor lighting to match screen brightness, thereby reducing the stimulation of screen glare to the eyes. For example, when using a computer at night, intelligent lighting can automatically dim to avoid strong environmental light forming a stark contrast with screen brightness, causing eye fatigue. Intelligent lighting can also be combined with sensors or timer functions to remind users to rest by changing the light color or brightness after prolonged eye use, preventing overuse of the eyes. For dry eye patients, specific lighting modes can be preset, such as reducing blue light components and providing more uniform light distribution, to alleviate the burden on the eyes. It is recommended to select light sources with low blue light or adjustable blue light components. Set appropriate brightness and color temperature according to different activity scenarios and personal needs. Avoid frequent changes in light, especially drastic switches in brightness or color temperature.

On the hardware level, it is necessary to select lighting devices with high-frequency PWM dimming [22], or use DC dimming, apply anti-glare coatings, and use reflectors. On the software level, the circadian rhythm adjustment mode—sleep-assisting display can effectively enhance users' visual experience in night-time and low-light environments. It can also regulate melatonin secretion, helping us sleep better.

5. RECOMMENDATIONS

5.1 Lighting Manufacturers' Role in Enhancing User Awareness and Education

Poor lighting is one of the significant factors that induce dry eye syndrome. As providers of lighting products to end-users, lighting manufacturers also bear the social responsibility of minimizing the potential harm caused by these products. Centering on user experience and in collaboration with the field of ophthalmology, manufacturers should focus on user eye health, disseminate knowledge about dry eye, and develop lighting products with dry eye protection features to offer users a healthy and comfortable experience. Specific recommendations are as follows:

1) Establish Communication Channels with Users:

- User Feedback Collection: Actively gather feedback from users with dry eye syndrome through various channels, such as online surveys, customer service inquiries, and social media platforms. This feedback should be systematically analyzed and relayed to the R&D department for specialized research.
- Regular User Interviews: Organize periodic interviews with dry eye patients to gain insights into their experiences and needs regarding lighting products.
- Social Media Interaction: Utilize social media platforms to engage with dry eye patients, respond to their inquiries, and gather their suggestions for product improvement.

2) Develop a Research Team with Ophthalmological and Ergonomic Expertise:

- Interdisciplinary Team Formation: Assemble a team of experts with backgrounds in ophthalmology and human factors engineering to conduct comprehensive research on the physiological mechanisms underlying eye health and to develop lighting products that reduce the risk of dry eye.

- Professional Laboratory Establishment: Set up a laboratory equipped for ophthalmological research and capable of verifying the eye-protective optical characteristics of lighting products.

-Product Prototyping: Based on user feedback and research findings, design and test prototypes of lighting products with features aimed at reducing dry eye risk, such as blink monitoring and reminders, and adjustable color temperature.

3) Collaborate Closely with Ophthalmology Departments and Medical Schools:

- Joint Research Projects: Apply for research grants and initiate collaborative projects to explore the relationship between the use of electronic products and the incidence of dry eye syndrome.

- Regular Academic Exchanges: Organize regular academic seminars to share research findings and advance the academic frontier in the field of dry eye prevention and treatment.

4) Actively Participate in and Support Dry Eye-Related Academic and Public Awareness Activities:

- Sponsorship of Academic Conferences**: Sponsor and participate in academic conferences related to dry eye syndrome to facilitate the dissemination of the latest research findings among experts in the field.

- Public Awareness Campaigns**: Organize public awareness events where experts can share knowledge on the prevention and treatment of dry eye syndrome, and invite users to participate free of charge, either online or offline.

5) Provide Product Recommendations and Usage Guidance for Users with Dry Eye Symptoms:

- Online Product Recommendations**: On the company's official website and e-commerce platforms, recommend products suitable for users with dry eye syndrome and provide detailed usage instructions.

- In-Store Staff Training: Train sales personnel in physical stores to offer professional product recommendations and usage advice tailored to the needs of users with dry eye syndrome.

5.2 Clinical Prevention Recommendations and Guidance for Dry Eye Syndrome

Dry eye syndrome is a common ophthalmological condition characterized by symptoms such as dryness, foreign body sensation, and blurred vision. The following are some clinical prevention recommendations:

1) Improve Eye-Use Habits:

- Follow the "20-20-20" rule: Every 20 minutes, look at an object 20 feet (approximately 6 meters) away for at least 20 seconds. Avoid prolonged continuous use of electronic screens and ensure regular eye rest. When reading, ensure adequate lighting and avoid using your eyes in overly dim or bright environments. It is also advisable to take a break every 40 minutes to look into the distance for about 10 minutes, allowing your eyes to rest fully.

2) Increase Indoor Humidity:

- Avoid staying for extended periods in environments with rapid air circulation, as dry conditions can lead to rapid evaporation of eye moisture [23]. Using a humidifier to maintain indoor humidity levels between 40% and 60% is recommended, especially during dry seasons or when using air conditioning or heating.

3) Dietary Recommendations:

- Maintaining adequate fluid intake helps to balance the body's hydration, thereby alleviating symptoms of eye dryness. Consuming foods rich in vitamins A, C, and E, as well as Omega-3 fatty acids [24], such as green leafy vegetables, carrots, fish, and nuts, can contribute to maintaining eye health.

4) Lifestyle Adjustments:

- Avoid prolonged use of contact lenses, as extended wear may interfere with the natural tear secretion of the eyes. It is suggested to reduce wearing time or opt for contact lenses with better oxygen permeability. Ensure sufficient sleep, as inadequate sleep can exacerbate eye fatigue and dryness.

6. SUMMARY AND OUTLOOK

6.1 Current Status and Challenges of Dry Eye Issues

The current status and challenges of dry eye problems are more severe under unhealthy lighting conditions. Unhealthy lighting, especially that with high blue light, high brightness, and flickering, can increase the burden on the eyes, accelerate tear evaporation, and irritate the ocular surface, thereby exacerbating dry eye symptoms and increasing the incidence of dry eye syndrome. Prolonged exposure to such environments can even lead to the gradual onset of dry eye symptoms in individuals who did not previously have the condition. People who use electronic screens for extended periods (such as office workers and students), those with pre-existing ocular conditions (such as meibomian gland dysfunction [25] and conjunctivitis), and the elderly are more susceptible to developing or worsening dry eye problems under unhealthy lighting. Many office spaces and school classrooms have suboptimal lighting conditions, characterized by insufficient illuminance, uneven illuminance distribution, excessively high color temperature, and flickering, all of which can have adverse effects on the eyes and increase the risk of developing dry eye syndrome. Additionally, many individuals lack sufficient awareness of the hazards of unhealthy lighting and fail to recognize the relationship between light quality and dry eye syndrome, thereby neglecting the improvement of the lighting environment.

Under unhealthy lighting conditions, dry eye symptoms may be amplified or masked, making it more difficult for physicians to accurately assess the severity and type of dry eye syndrome, which in turn affects the selection of appropriate treatment plans. Even if pharmacological or other therapeutic interventions are employed, the effectiveness of the treatment can be significantly reduced if the patient remains in an unhealthy lighting environment, and may even lead to relapse or worsening of the condition. Improving the lighting environment often requires a certain investment of cost and effort, such as replacing lighting fixtures and adjusting the lighting layout, which may not be feasible in some cases, especially for public places or older buildings. The current lighting standards for addressing dry eye issues are still not comprehensive enough, lacking detailed guidance for different populations and scenarios, and thus failing to meet practical needs. The education and publicity regarding the impact of unhealthy lighting on dry eye syndrome are also insufficient and need to be further strengthened to raise public awareness and attention.

In summary, dry eye problems are more prominent and pose greater challenges for diagnosis and treatment under unhealthy lighting conditions. Improving the lighting environment is an important measure for the prevention and alleviation of dry eye syndrome and requires the joint efforts of individuals, enterprises, and governments. It is essential to promote dry eye-friendly healthy lighting devices, formulate and improve relevant standards, and enhance public education and publicity to effectively reduce the risk of dry eye syndrome and protect people's eye health.

6.2 Core Value of Lighting Equipment in Dry Eye Management

The core value of lighting equipment in dry eye management lies in providing comfortable and safe illumination to reduce visual fatigue, alleviate dry eye symptoms, prevent the occurrence of dry eye, and thereby protect visual health and improve the quality of work and life. This is mainly reflected in the following aspects:

Optimization of Dimming Technology: By employing technologies such as flicker-free dimming, natural light simulation, low blue light radiation, and dynamic color temperature adaptation, eye fatigue can be reduced.

User Behavior Intervention: Based on AI algorithms, monitoring of eye use duration can be conducted, with active reminders for rest or activation of eye-protection modes.

Environmental Adaptability: By integrating ambient light sensors and humidity detection modules, display parameters can be dynamically adjusted to lower the risk of dry eye.

6.3 Integration of Technological Innovation and Medical Needs

Interdisciplinary cooperation among the medical, optical, electronic, material, and ergonomic fields has provided a new paradigm for the prevention and control of dry eye syndrome. For example:

Intelligent Diagnosis: By capturing indicators such as blink frequency and tear film break-up time (TFBUT) through eye-tracking sensors and combining them with AI models, early screening for dry eye can be achieved [26].

Personalized Intervention: Based on user eye-use data, health reports are generated to recommend personalized eye-protection plans (such as suggestions for the use of artificial tears and adjustments to eye-use habits).

Medical Referral: By linking lighting devices with wearable devices and conducting behavior detection at the terminal, relevant risk alerts are provided to users based on the results, and the most appropriate medical services are recommended to achieve the optimal timing for medical intervention.

6.4 Social Value and Industry Responsibility

The promotion of dry eye-friendly lighting has significant social benefits:

Economic Benefits: By reducing the incidence of dry eye through preventive design, medical expenses and productivity losses can be reduced. Studies have shown that the average annual medical costs for dry eye patients are significantly higher than those for healthy individuals.

Public Health: Through the built-in health functions in lighting product apps, companies can disseminate knowledge about ocular surface health to hundreds of millions of users, contributing to public health education.

Sustainable Development: This aligns with the United Nations' Sustainable Development Goal of "ensuring healthy lives and promoting well-being for all at all ages."

6.5 Future Development Directions

6.5.1 Technological Trends

Deep Integration of AI and 5G: Real-time eye health monitoring through edge computing, combined with cloud platforms to provide remote medical advice.

Application of Smart Sensors: Ambient light sensors accurately perceive ambient light [27], automatically adjusting the brightness and color temperature of lighting devices to seamlessly integrate with the surrounding light. Eye-tracking sensors monitor real-time eye use status, such as blink frequency and pupil size, and dynamically adjust lighting parameters based on these data to provide more proactive eye protection functions.

Breakthroughs in Materials Science: Developing new types of optical materials to achieve more precise optical control and superior optical performance.

6.5.2 Suggestions for Ecosystem Construction

Standardization: Promote the development of unified industry standards for dry eye-friendly lighting technology (such as flicker rate and blue light radiation thresholds).

Interdisciplinary Collaboration: Establish a regular communication mechanism among the medical, optical, electronic, material, and ergonomic fields and policymakers to accelerate the clinical translation of technology.

User Education: Through product manuals, emphasize the importance of maintaining good eye use habits, such as the "20-20-20" eye protection rule (every 20 minutes, look at an object 20 feet away for 20 seconds) [28], and maintaining an appropriate viewing distance and posture.

7. CONCLUSION

Dry eye-friendly healthy lighting devices are the product of technological progress. As people's awareness of eye health and lighting quality continues to increase, and research into eye diseases such as dry eye syndrome deepens, lighting technology is also evolving to better meet the demand for healthy lighting. Dry eye-friendly healthy lighting devices are a comprehensive reflection of technological advancements in multiple fields, including optics, electronics, materials, and ergonomics. They aim to provide users with a more comfortable and healthy visual environment and to prevent and alleviate eye problems such as dry eye syndrome. With the continuous development of technology, it is believed that more innovative technologies will be applied to dry eye-friendly lighting devices in the future, offering better protection for people's eye health.

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