

White Paper on Lighting Health -Friendly for Eye Fatigue

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ABSTRACT

Visual fatigue has emerged as a significant public health concern in the digital era, exacerbated by prolonged exposure to electronic screens and suboptimal lighting conditions. This review synthesizes current research on the etiology, epidemiology, and technological interventions for visual fatigue, with a focus on the role of lighting design in prevention and mitigation. The paper begins by defining visual fatigue as a multifactorial syndrome characterized by ocular discomfort (e.g., dryness, photophobia) and visual disturbances (e.g., blurred vision), often accompanied by systemic symptoms like headaches. Epidemiological data reveal particularly high prevalence (50-90%) among office workers and students, driven by environmental factors including improper lighting (23% of cases), excessive blue light exposure, and screen flicker. Notably, 71.3% of dry eye patients exhibit concurrent visual fatigue, underscoring the bidirectional relationship between ocular surface health and accommodative strain. A critical analysis of lighting parameters identifies four key aggravating factors: (1) non-adaptive brightness (either <100 lux or >1000 lux), (2) high-color-temperature light (>5000K) with elevated blue wavelengths (450-490nm), (3) perceptible flicker (<80Hz), and (4) non-uniform illumination creating >3:1 contrast ratios. These factors disrupt pupillary reflexes, accelerate tear film evaporation (blink rate reduction by 60% in dim light), and induce ciliary muscle spasms.

1 Introduction

1.1 Definition and Background of Visual Fatigue

Visual fatigue, also known as asthenopia, is a syndrome characterized by visual disturbances and ocular discomfort, with or without systemic symptoms, resulting from excessive visual demands that exceed the eye's functional capacity. Its influencing factors and clinical manifestations are complex and diverse [1]. Common symptoms include dry eyes, eye soreness, eye strain, photophobia, tearing, blurred or double vision, headaches, and dizziness. In recent years, with societal development and lifestyle changes, the prevalence of visual fatigue has increased significantly. It is often categorized as part of "digital eye strain" [2], a typical health side effect of the digital lifestyle. Risk factors such as poor lighting conditions (excessive brightness or dimness), prolonged screen exposure, excessive reading, lack of outdoor activities, and insufficient sleep greatly elevate the risk of visual fatigue. With the rapid advancement of lighting technology, lighting devices have become ubiquitous in workplaces, educational settings, and entertainment venues. Prolonged near-vision tasks under suboptimal lighting conditions have led to a marked rise in the incidence of visual fatigue. Visual fatigue not only compromises personal comfort and reduces work or study efficiency but also interacts with psychological burdens such as anxiety and depression, forming a vicious cycle that severely impacts patients' quality of life and imposes significant economic costs on society and healthcare systems.

1.2 The Impact of Lighting on Visual Fatigue

Visual fatigue is a common ocular discomfort symptom exacerbated by prolonged exposure to inappropriate lighting conditions. In modern society, individuals are constantly exposed to various lighting environments, whether fluorescent lights in offices, LED lights at home, or light emitted from electronic screens—all of which can trigger visual fatigue [3]. Therefore, proper lighting design is crucial for mitigating visual fatigue.

First, inappropriate lighting brightness is one of the most direct factors contributing to visual fatigue. Although the human eye has a strong capacity to adapt to light, prolonged exposure to excessively bright or dim conditions can overburden the eyes. Under bright light, the pupil constricts to reduce light entry, keeping the ciliary muscles in a state of sustained tension, akin to holding a heavy object for an extended period, which inevitably leads to muscle fatigue [4]. Simultaneously, retinal photoreceptors, particularly cone cells, become overstimulated, accelerating energy consumption and inducing photochemical toxicity, resulting in symptoms such as blurred vision, eye pain, and photophobia. Conversely, in dim lighting, the eye must exert more effort to focus, with the pupil dilating to capture more light. This also forces the ciliary muscles to remain contracted for prolonged periods, easily triggering visual fatigue symptoms like dryness, irritation, decreased visual acuity, and reading difficulties [5]. Whether from glaring sunlight or straining to read in a dark corner, these conditions deplete the eye's energy reserves unnoticed.

Second, light color temperature significantly influences visual fatigue. High color temperature (typically above 5000K, emitting cool white or bluish light) is often referred to as "cool light." While such light may enhance alertness during daytime or tasks requiring high concentration, its high blue light component poses risks. Blue light, with its higher energy, penetrates the lens and reaches the retina. Prolonged exposure to intense blue light suppresses melatonin secretion, disrupts circadian rhythms, and may cause potential retinal damage while increasing susceptibility to visual fatigue and discomfort [6]. Many electronic screens (e.g., computers, smartphones, tablets) emit blue light-rich radiation, explaining why prolonged device use often leads to eye strain [7]. In contrast, low color temperature (below 3000K, emitting warm yellowish or reddish light), termed "warm light," creates a soothing ambiance with minimal eye irritation, making it more suitable for nighttime or relaxation. Mid-range color temperature (e.g., around 4000K) offers a balanced compromise. Thus, for prolonged near-vision tasks, selecting warm or neutral color temperature lighting helps reduce visual stress.

Third, light flicker, though often overlooked, is a "hidden culprit" behind visual fatigue. Not all light sources are

perfectly stable; many traditional fluorescent lamps, energy-saving bulbs, and even low-quality LED lights exhibit visible or invisible flicker. Visible flicker refers to perceptible brightness fluctuations, typically below 80Hz. When flicker frequencies range between 80–1250Hz, they become imperceptible to the human eye but detectable by devices like cameras. Although imperceptible, such flicker forces the eye's regulatory system to continuously micro-adjust, akin to watching a rapidly flickering screen. This sustained, subtle adjustment consumes substantial energy, easily leading to visual fatigue, headaches, or even afterimages [8].

Moreover, glare is another critical factor exacerbating visual fatigue [9]. Glare occurs when inappropriate brightness distribution or extreme contrast within the visual field causes discomfort or reduces object visibility. Direct glare (e.g., staring at a light source) and indirect glare (e.g., reflections from glossy surfaces) disrupt the visual system's adaptive equilibrium, triggering discomfort, reduced acuity, or even temporary blindness. For computer users, screen brightness, contrast with ambient lighting, or desk reflections can create glare sources, significantly increasing visual fatigue risk during prolonged exposure.

Lastly, lighting uniformity is equally important. Uneven illumination—such as a desk partially lit and partially shadowed or stark brightness contrasts around screens—forces the eyes to constantly readjust focus, straining the ciliary muscles and increasing pupil modulation frequency. This instability leads to visual fatigue. Ideal lighting should be uniformly soft, avoiding sharp brightness contrasts.

2 Current Status of Visual Fatigue

2.1 Epidemiological Data on Visual Fatigue

The prevalence of visual fatigue varies significantly across studies due to differences in design, target populations, diagnostic criteria, and assessment methods, making it challenging to establish a globally consistent rate [10]. However, multiple studies concur on a clear trend: visual fatigue is highly prevalent, especially among specific groups. Populations engaged in prolonged near-vision tasks—such as office workers, IT professionals, designers, editors, and students—report particularly high rates [11].

Regional surveys indicate that 50–90% or more of these individuals experience visual fatigue symptoms. For instance, studies on office workers consistently find that over two-thirds report varying degrees of visual fatigue. Students, especially in primary, secondary, and higher education, face elevated risks due to academic pressure, prolonged reading, and digital device use (e.g., tablets, smartphones) [12]. A university student survey revealed that over 80% reported visual fatigue symptoms. With an aging population, older adults also experience increased visual fatigue due to declining accommodative ability, cataracts, or dry eye syndrome. Certain occupations—precision instrument operators, drivers (prolonged focus on road or dashboards), and ophthalmologists (performing delicate surgeries)—also face higher risks.

2.2 Major Risk Factors for Visual Fatigue

Risk factors for visual fatigue primarily involve visual behaviors, environmental conditions, ocular or systemic health, and include:

(1) Visual Behaviors:

① Prolonged near-vision tasks: Extended reading, smartphone use, computer gaming, or fine handiwork require sustained accommodative effort, straining the ciliary muscles. Excessive screen time ("digital eye strain" or "computer vision syndrome") is a prevalent modern trigger [13].

② Improper screen use: Unsuitable brightness/contrast (too bright/dim or extreme contrast with ambient light) [14]; suboptimal screen positioning (too close/far or improper height—ideally at or slightly below eye level); screen flicker or low refresh rates (older or low-quality monitors); blue light exposure (though its direct role in visual fatigue is debated, prolonged exposure may disrupt sleep [15], indirectly affecting ocular comfort).

③ Reduced blink rate: Screen use or intense focus often unconsciously decreases blinking, reducing ocular surface lubrication.

④ Incomplete blinking: Concentration or contact lens wear may lead to partial blinks, impairing meibomian gland lipid

secretion. This compromises tear film stability, accelerating evaporation and exacerbating fatigue.

⑤ Poor posture: Incorrect head or body alignment may cause neck/shoulder tension, indirectly affecting ocular comfort.

⑥ Lack of breaks: Failure to follow the "20-20-20 rule" (every 20 minutes, look at an object 20 feet away for 20 seconds) [16].

(2) Environmental Factors:

① Poor lighting: Excessive brightness (direct sunlight) or dimness (using devices in darkness) strains the eyes; lack of natural light also contributes. Glare from windows, lamps, or screen reflections forces squinting and excessive focusing effort.

② Dry environments: Air-conditioned/heated rooms or arid climates accelerate tear evaporation, inducing dry eye and worsening fatigue.

③ Poor ventilation: Accumulated dust, smoke, or irritants in stagnant air.

(3) Ocular Factors:

① Uncorrected or undercorrected refractive errors [17]: Myopia, hyperopia, or astigmatism necessitate excessive focusing effort. Worn/scratched lenses, loose frames, or lens stress can also blur or distort vision.

② Heterophoria or accommodative-convergence dysfunction [18]: Near tasks require coordinated lens accommodation and binocular convergence. Poor coordination rapidly induces fatigue.

③ Dry eye syndrome [19] or other ocular diseases: Inadequate tear quantity/quality reduces lubrication, causing dryness, pain, and fatigue. Eyelid abnormalities or scarring may exacerbate symptoms.

④ Age-related decline: Presbyopia reduces accommodative ability, increasing fatigue susceptibility.

(4) Systemic Factors:

① Sleep deprivation or poor quality: Sleep is critical for ocular recovery; chronic deficiency accumulates fatigue.

② High stress: Mental tension may sustain periocular muscle contraction.

③ Nutritional imbalances: Deficiencies in eye-health nutrients (e.g., vitamins [20], lutein).

④ Certain diseases: Thyroid disorders, anemia, or autoimmune conditions may affect ocular health.

2.3 Association Between Lighting Product Usage and Visual Fatigue Epidemiology

Lighting products are indispensable in daily life, and their quality, type, and usage directly impact visual comfort and health. As a common visual issue, visual fatigue's epidemiology is strongly influenced by lighting environments. Surveys estimate that 20–30% of the global population experiences varying degrees of visual fatigue, with higher rates in specific groups. For instance, office workers, students, night-shift workers, and those frequently in poor lighting report significantly elevated incidence compared to the general population.

2.4 Common Lighting Device Behaviors Among Visual Fatigue Patients

Through user interviews, surveys, and social media content analysis, we observe that visual fatigue patients often use lighting devices in dim environments or set screens to very low brightness, believing normal/brighter light exacerbates discomfort. However, excessive contrast from low brightness may strain focus. Some patients are highly sensitive to glare/reflections, adjusting device angles, closing curtains, or redirecting lights to avoid reflections. While this minimizes direct glare, improper adjustments may cause uneven screen displays or uncomfortable postures. Others prefer fixed-color-temperature, stable-brightness lighting, avoiding smart bulbs' dynamic modes or auto-adjustment, fearing added adaptation burden. However, moderate light variation may maintain

alertness—the key lies in appropriate intensity and frequency.

Visual fatigue patients exhibit heightened sensitivity and personalized adjustments toward lighting quality (brightness, glare, flicker, color temperature, CRI). Their attempts to alleviate discomfort through lighting modifications are often based on subjective perceptions, sometimes inadvertently worsening symptoms.

3 Industry Standards and Best Practices

3.1 Expert Consensus and Research Summary: Lighting Devices and Visual Fatigue—Current Evidence and Advances

The 2024 edition of the Chinese Expert Consensus on Visual Fatigue Diagnosis and Management [1] states that visual fatigue arises from intertwined ocular, systemic, and psychological factors. Among ocular factors, dry eye—strongly linked to visual fatigue—affects 71.3% of dry eye patients, while 51.4% of visual fatigue cases meet dry eye criteria. Poor lighting (excessive brightness/dimness, glare) promotes dry eye development, thereby inducing visual fatigue. Moreover, abnormal light stimuli in work/living environments (e.g., improper lighting) can trigger ocular discomfort, dizziness, neck/shoulder pain, and other systemic symptoms.

3.1.1 Advances in Pathogenesis Research

(1) Pupillary strain: In dim environments, prolonged pupil dilation to capture more light overworks the pupillary dilator muscles, causing fatigue akin to sustained muscle contraction elsewhere.

(2) Accommodative spasm/fatigue: Dim light challenges focus, requiring excessive ciliary muscle effort for near tasks, leading to spasm, soreness, or transient blur.

(3) Reduced/incomplete blinking: Studies show dim environments or screen focus reduce blink rates and completeness, accelerating tear evaporation and causing dryness, redness, and irritation—hallmarks of visual fatigue.

4 Lighting Device Design and Calibration

4.1 Smart Device Feature Recommendations for Visual Fatigue Users

4.1.1 Current Analysis of Eye Protection Technologies in Smart Devices

Contemporary lighting devices present multiple challenges to ocular health regarding brightness, color temperature, color rendering index (CRI), flicker, and glare. For instance:

Low ambient light forces pupillary dilation to capture more light, increasing accommodative burden. Dim lighting blurs object contours, requiring excessive focusing effort that induces visual fatigue.

Excessive brightness stimulates pupillary constriction, similarly straining accommodation. Prolonged exposure may cause photophobia, lacrimation, and eye pain—classic symptoms of asthenopia.

Glare disrupts vision by triggering squinting or frequent blinking, significantly elevating fatigue risk and potentially inducing headaches [21].

Fortunately, manufacturers are increasingly prioritizing ocular health, with recent advancements in hardware and software innovations:

Hardware Innovations:

Optical Structure Optimization [23]: Polyhedral or freeform lenses utilize complex geometries to scatter and redirect light, achieving wide-area uniform illumination while controlling beam angles to avoid harsh glare. Diffusers made of PMMA/PC with frosted, pearlescent, or micro-structured surfaces enhance light diffusion via surface irregularities.

Spectral Control: Multi-chip LED arrays combine red/green/blue (and optionally yellow/violet) emitters, enabling precise spectral tuning through brightness modulation. Advanced phosphor formulations or blue-light-cut filters [24] reduce 450–490 nm high-energy blue light exposure [25].

Dimming Technology:

High-frequency PWM dimming (beyond visual persistence thresholds) minimizes iris muscle workload by simulating

DC-like stability.

DC dimming eliminates flicker entirely via current adjustment, reducing ocular irritation.

Natural Light Simulation [26]: Full-spectrum LEDs mimic solar radiation by enhancing red components, improving CRI (>95), and stabilizing output. This aligns circadian rhythms, mitigates fatigue/dry eye symptoms [27], and boosts productivity in offices/classrooms.

Software Innovations:

Spectral Management: Algorithm-driven LED channel control enables dynamic spectral matching beyond fixed color temperatures.

Adaptive Brightness: Ambient light sensors maintain optimal workspace illuminance (e.g., 300–500 lux) via real-time adjustments. Smooth transitions prevent abrupt brightness shifts.

Color Management: Context-aware color temperature:

Neutral (4000K) for work/study.

Warm (2700–3500K) for nighttime relaxation.

Behavioral Interventions: Eye-tracking monitors blink rate, viewing distance, and posture. Features include:

Distance alerts (<40 cm triggers warnings).

Blink reminders (if rate falls below 10/min).

4.1.2 Recommended Features for Visual Fatigue-Friendly Devices

Building on epidemiological insights and existing technologies, ideal devices should incorporate:

(1) Reduced Harmful Blue Light

Blue light (especially 450–490 nm) suppresses melatonin, disrupts sleep, and exacerbates dry eye by reducing blink rates [28]. Scattered blue light also degrades retinal image quality. Threshold-controlled blue light emission is essential.

(2) Flicker Mitigation

Even imperceptible flicker (80–1250Hz) forces continuous

ocular micro-adjustments, causing strain, blurred edges, and cognitive distraction. Prioritize flicker-free LEDs compliant with IEEE Std 1789-2015 or ENERGY STAR standards.

(3) High CRI (≥ 90)

Low-CRI sources (<80) distort colors, accelerating fatigue. High-CRI lighting (≥ 90 , ideally ≥ 95) ensures natural color perception.

(4) Blink Rate Enhancement

Complete blinks are critical for tear film redistribution. Devices should monitor blink frequency and prompt users when rates drop below safety thresholds (e.g., <12 /min).

(5) Proximity Alerts

Prolonged near-work (<30 cm) induces accommodative spasm and convergence fatigue. Distance sensors can enforce healthy viewing habits.

(6) Context-Aware Adaptive Lighting

Smart systems should auto-adjust parameters (brightness/color temperature) based on:

Time of day (6500K mornings \rightarrow 2700K evenings).

Activity (reading vs. relaxation).

This reduces glare and adaptation stress while supporting circadian health.

Under China's "Healthy China 2030" initiative, manufacturers must embed visual fatigue prevention into core designs through interdisciplinary collaboration (ophthalmology, ergonomics).

4.2 Design Principles for Visual Fatigue Users

4.2.1 Technical Approaches and Calibration Examples

Natural light simulation: Full-spectrum LEDs mimic sunlight to reduce strain.

Blue-light-reduced modes: Lower blue light intensity alleviates dryness and irritation.

Dynamic color temperature: Auto-adjustment synchronizes

with ambient light.

High-frequency PWM/DC dimming: Eliminates flicker-induced fatigue.

Optical homogenization: Lenses/diffusers ensure uniform illumination without harsh contrasts.

Emerging technologies (e.g., AI-driven adaptive systems) warrant further exploration.

4.2.2 Human-Computer Interaction Examples

Commercial solutions already integrate:

Real-time posture/distance alerts.

Blink frequency monitors with haptic/visual reminders.

4.3 Lighting Calibration Guidelines for Visual Fatigue

Severe Cases: Adopt smart lighting systems with:

Work/study: 300–500 lux task lighting (≥ 500 lux within 30 cm), ambient/task ratio $< 3:1$.

Night: 100–200 lux; avoid screen use in darkness.

Color Temperature:

Day: 3000–4000K (neutral).

Night: ≤ 3000 K (warm).

CRI: Prioritize ≥ 90 sources.

Uniformity:

Position task lights to avoid shadows (left-front for right-handed users).

Supplement with ambient lighting.

Add bias lighting behind screens to reduce contrast.

Automation:

Light sensors for real-time adjustments.

Scheduled dimming reminders (e.g., 30-minute intervals).

5 Recommendations

5.1 Manufacturer-Led User Education

Lighting companies must promote awareness via:

Online Channels:

Social media campaigns (WeChat, Douyin, Bilibili) on fatigue prevention.

Collaborations with health/tech influencers.

Educational portals with self-assessment tools.

Offline Channels:

Partnerships with ophthalmology clinics for workshops.

Retail demos in electronics/home stores.

University outreach programs.

5.2 Clinical Prevention Strategies

(1) Visual Hygiene:

20-20-20 rule (20-second breaks every 20 minutes).

Screen distance: 50–70 cm; top aligned with/near eye level.

Conscious blinking (10–12/min).

(2) Environment Optimization:

Balanced ambient/screen brightness.

Anti-glare screens; humidity $> 40\%$.

(3) Lifestyle:

Sleep hygiene; omega-3/vitamin-rich diets [30].

Warm compresses for dry eyes.

(4) Regular Eye Exams:

Correct refractive errors promptly.

Seek professional care for persistent symptoms.

6 Summary and Outlook

6.1 Current Challenges

Under-recognition: Often dismissed as transient discomfort.

Complex interventions: Habit modification and environmental control are difficult.

Diagnostic limitations: Subjective symptoms overlap with dry eye/refractive errors.

Economic burden: Reduced productivity and healthcare costs [32].

6.2 Lighting's Pivotal Role

Future devices must integrate:

Flicker-free, spectrally optimized illumination.

AI-powered behavioral monitoring.

Environmental adaptability (humidity/light sensors).

6.3 Med-Tech Convergence

Examples include:

AI screening: Eye-tracking for early fatigue detection.

Personalized interventions: Customized reports linking device data to clinical advice.

6.4 Societal Impact

Economic: Lower medical costs via prevention.

Public health: Scalable education through smart devices.

Sustainability: Energy-efficient designs align with UN SDGs.

6.5 Future Directions

Multisensory health ecosystems: Integrated lighting/air quality/sound systems.

AI + 5G: Real-time tele-ophthalmology support.

Advanced sensors: Autonomous adjustments via eye-tracking/environmental data.

Material science: Novel optical substrates for precision control [34].

Ecosystem Building:

Standardize metrics (e.g., flicker thresholds).

Foster cross-disciplinary R&D (medicine/engineering).

User-centric manuals emphasizing the 20-20-20 rule.

7 Conclusion

In our digital era, visual fatigue demands urgent attention. "Fatigue-friendly" lighting—characterized by uniformity, adaptability, and minimal glare—combined with proper habits, can safeguard ocular health. This requires collective action from individuals, workplaces, and manufacturers to harmonize technological innovation with physiological needs.

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