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Performance Trade-offs of Mainstream Display Technologies and Their Ocular Impacts

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Abstract. With the spread of digital displays in recent years, people have begun to pay more attention to their eyes. Engineering Analysis of Main Display Technologies: Liquid Crystal Display (LCD), Organic Light-Emitting Diode (OLED) and Micro Light-Emitting Diode (MicroLED), and Associated Risks to Eye Health. According to the three criteria of blue-light hazard, temporal light modulation (flicker) and circadian rhythm disruption, these technologies are judged by foreign standards. We have connected the above risk factors to the main ideas of each display. LCDs can be hazardous due to blue-peaked LED backlights and low-frequency PWM dimming. OLEDs have a high-contrast display but often use the same PWM strategy at low brightness. MicroLEDs present the greatest potential for mitigating these risks with highly tunable spectra and flicker-free current-driving capabilities, though their high brightness must be managed. Therefore, the safety of the eyes is not an intrinsic property of the display type but rather the result of specific engineering measures in the driver circuit and spectral design. Good-design OLED and MicroLED technology can reduce eye strain significantly, but circuit-level implementation is the main problem.

Keywords: Display Technology; Ocular Health; Flicker; Blue-Light Hazard.

1. Introduction

Digital Screens are now common in daily life. With increased productivity, prolonged exposure to screens is now frequently linked with Digital Eye Strain (DES); other symptoms include headaches, fatigue, dryness and blurred vision, and it affects all age groups [1]. Although the mechanism of DES is not clear, three device-controllable factors have been consistently identified as the main reasons: high-energy blue light exposure, temporal light modulation (flicker), and the stimulating effect of light on circadian rhythms [1].

A system of consensus international standards will be used to quantify the above factors. This paper studies the risk of photochemical damage under the blue-light hazard weighting function in IEC 62471. Based on the criteria for frequency and modulation depth in IEEE 1789, flicker risk will be determined. Finally, we will investigate the non-visual, biological effects of light on the body's internal clock by means of melanopic metrics in CIE S026. We can compare the image quality and physiological-relevant output of LCD, OLED and MicroLED technologies in this way [2].

The basic structure of the technology for each display determines how it works optically. LCDs use LED backlights filtered by liquid-crystal shutters; OLEDs are self-emissive organic diodes; and MicroLEDs are self-emissive inorganic diodes. These differences affect both the contrast and the response speed, and more significantly, how dimming is realised (usually by Pulse-Width Modulation or analogue DC current); therefore, flicker exposure varies accordingly. Therefore, in this study, we link the underlying driver circuits and spectral characteristics of each display to the established health standards, focusing on the effects of prolonged use at typical viewing distances, and do not examine acute photochemical injury that modern consumer displays are designed to avoid.

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2. Theoretical Foundations

2.1. Why displays can stress the eyes

Blue-light photochemical hazard: Retinal risk is assessed by blue-light weighted radiance LBL_BLB using B(λ)B(λ)B(λ), with a peak at 435–440 nm. Typical consumer displays fall within RG0-RG1 (no/low risk) at normal use, but SPDs with strong short-blue peaks increase LBL_BLB per given luminance and reduce the safe exposure margin [3].

Temporal Light Modulation (flicker): PWM and other TLM below ~1-2 kHz with a relatively large modulation depth are associated with discomfort, headaches and reduced visual performance in sensitive individuals; IEEE 1789 specifies recommended regions based on frequency-depth trade-offs.

Circadian stimulation: Evening exposure to high melanopic content suppresses melatonin and increases alertness independently of RGB "colourfulness", thus spectral shaping.

2.2. Display principles

LCD (liquid-crystal + LED backlight). A white (often blue-pumped) LED backlight passes through diffusers, polarizers, LC shutters and RGB colour filters. Brightness control often uses backlight PWM at hundreds of Hz, and some high-end sets have added mini-LED local dimming for better contrast/HDR. Driver ICs (boost LED strings + current sinks) generally have a PWM input; datasheets list supported PWM bands from a few hundred Hz and above, unless "PWM-to-DC" dimming is employed.

OLED (Self-emissive). Each pixel is a current-driven organic diode gated by a TFT pixel circuit (e.g., 2T1C/3T1C with a storage capacitor and threshold-voltage compensation). OLEDs have microsecond-level response and near-infinite native contrast (per-pixel off), but many mobile implementations dim via PWM at low brightness, increasing TLM exposure if the frequency/modulation depth are not optimal [4].

MicroLED (self-emissive inorganic). Micron-scale GaN/AlGaInP LEDs on active-matrix backplanes (LTPS/oxide/CMOS) are driven by current sources; spectra can be engineered directly (RGB) or through colour conversion. MicroLEDs have a high-brightness and fast-current-control characteristic; thus, high-frequency PWM or true analog dimming can be used to control peak brightness and glare.

3. Performance Comparison and Eye-Safety Analysis

3.1. LCD

3.1.1. Display performance.

LCDs are still relatively common and are used in desktop monitors, laptops and other TVs. The two reasons for the relatively slow response time and low native contrast of liquid-crystal molecules with a global backlight have been inherent to them historically. Mini-LED backlight arrays with local dimming have recently been released to address the above problems. Divide the backlight into hundreds or thousands of control areas, reduce the light in dark areas, increase the light in bright highlight areas, and thus achieve a high-dynamic-range (HDR) contrast ratio of around 100,000:1 or more. Optical simulations published in SID and Optica journals have shown that zone-based dimming can achieve significantly higher perceptual contrast than the old edge-lit design.

Response time is still fundamentally LC-limited. A typical grey-to-grey switch is in the range of 2-10ms and causes motion blur during rapid changes. Overdrive voltage driving, scanning backlights and black frame insertion are typical ways to reduce the motion picture response time (MPRT). The above ways improve the clarity of moving pictures but often reduce brightness or cause flicker [5]. OLED and MicroLED are emissive technologies that operate at the microsecond level; therefore,

LCDs will be less suitable for high-speed applications such as gaming and VR. However, with high-zone-count mini-LED dimming, optimised liquid-crystal materials and improved optical films, LCDs are still very competitive for large-format HDR televisions.

3.1.2. Eye-impact analysis.

The two main problems for human factors engineering of LCDs are spectral composition and temporal light modulation (TLM).

Blue-light hazard: White LED backlights are generally based on blue GaN chips with yellow phosphors, and their emission peaks are around 440-460 nm. According to IEC 62471, the blue-light hazard is given by the weighted radiance $L_B = \int L\lambda(\lambda)B(\lambda)d\lambda$, and $B(\lambda)$ is maximum at 435–440 nm. Most office and consumer displays fall into risk groups RG0–RG1, meaning 'no risk' or 'low risk' at standard usage distances. The total exposure index will be different for various Spectral Power Distributions (SPDs) and correlated colour temperatures (CCTs). Panels with a high CCT (e.g., 7000K 'cool' white) naturally emit more short-blue light than warm-coloured ones, which may increase the long-term photobiological burden [6].

Flicker/TLM: Brightness modulation of LCDs is generally achieved by PWM of the LED backlight. Most of them have a frequency in the 200-500Hz range, some less expensive models are below 200Hz, and high-end monitors exceed 1kHz. In accordance with IEEE 1789, low-frequency PWM and high-modulation-depth operation are likely to cause discomfort, headaches and visual fatigue in sensitive individuals. According to the consumer report and laboratory test results, a relatively high PWM frequency (≥2kHz) will not flicker. Alternatively, DC dimming or filtered-PWM can be used to supply a constant current to the LEDs at a lower drive level [7]. These ways avoid flicker but need good heat dissipation to prevent colour changes. Illustrative LCD backlight dimming block is shown in Fig.1.

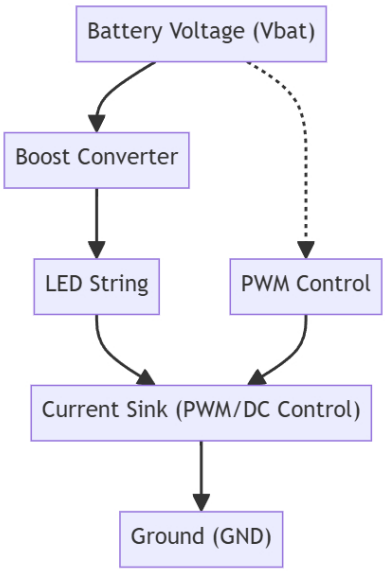

Fig. 1 Illustrative LCD backlight dimming block (Picture credit: Original)

Datasheets confirm that modern LED driver ICs support both high-frequency PWM and hybrid schemes. Thus, while LCD technology itself is not inherently 'eye-unfriendly,' the chosen driver configuration plays a decisive role in determining user comfort.

3.2. OLED

3.2.1. Display performance.

OLEDs are self-emissive devices that do not need a separate backlight, and each subpixel emits light independently. OLEDs have a very large native contrast ratio and can display black by turning off the corresponding pixels completely. The response speed is in the microsecond range; thus, it can

show the movement of high-speed videos, such as esports and VR, clearly and smoothly. OLEDs have a wide viewing angle, high colour saturation and flexible form factors (curved, foldable displays)[8].

OLEDs also have some problems. Peak Luminance has been lower than that of LCDs historically, but now high-definition HDR implementations exceed 1000 nits. Another defect is a shorter service life of the subpixels; blue OLEDs are more prone to degradation and burn-in. Compensation methods (e.g., pixel-shift algorithms, current equalization and software-level corrections) can address the above problems.

3.2.2. Eye-impact analysis.

Flicker/TLM: As OLED subpixels are current-driven, brightness is reduced by either analogue current control or PWM dimming. Many mobile phones employ PWM at a low brightness to preserve colour accuracy. Unfortunately, most PWM frequencies are between 240-480 Hz and are thus noticeable to sensitive individuals. Therefore, manufacturers have introduced 'eye comfort' or 'DC dimming' modes and doubled the PWM frequency to around 960Hz or higher. In accordance with IEEE 1789 recommendations, a relatively high frequency and a small modulation index are used.

Blue/Circadian Effects: OLED spectra can be engineered more flexibly than in LCDs. For example, software-enabled 'night mode' shifts emissions to longer wavelengths and reduces short-blue light output and melanopic stimulation in the evening. However, research on smartphone users has also shown that prolonged OLED reading can cause eye dryness and discomfort; thus, the theory of digital eye strain (DES) attributes this to extended task duration and visual demand rather than spectral risk alone.

Temporal Dithering (FRC): Some OLED panels have increased the number of bits and employed temporal dithering to enhance colour depth. This introduces high-frequency subframe toggling of the luminance or chromatic channel. Although it is not noticeable to most people, some users have reported discomfort; therefore, some professional monitors have added an optional FRC disable function.

In short, although OLED technology has good optical properties, care should be taken in the method of dimming, SPD tuning and dithering algorithms to avoid visual discomfort.

3.3. MicroLED

3.3.1. Display performance.

MicroLEDs are promising next-generation emission devices that combine the high-contrast, high-speed characteristics of OLEDs with the robustness and efficiency of inorganic LEDs. Each subpixel is a micro-LED made of GaN (blue/green) or AlGaInP (red) and is placed on an active-matrix backplane (LTPS, oxide TFT or CMOS). Laboratory prototypes have achieved luminance values of over 10,000 nits for micro-displays and several thousand nits for larger panels, far exceeding the current OLED and LCD technologies. MicroLEDs also have good colour purity, a wide colour gamut and excellent long-term stability without organic degradation [9].

The main problem is manufacturing difficulty; specifically, mass transfer and yield control at the micron level are challenging. Research continues on scalable bonding, repair and epitaxial strategies. Despite the above problems, industry roadmaps predict commercial consumer panels in the coming years.

3.3.2. Eye-impact analysis.

Blue-light hazard: MicroLEDs are fully emissive, so their SPD can be engineered by epitaxy or down-conversion layers. Therefore, the blue peak can be shifted or its intensity reduced to lower L_B compared with phosphor-pumped LCD backlights. As with other displays, consumer products are expected to fall into RG0–RG1 per IEC 62471 at normal usage distances. The main ergonomic

problem is glare at high luminance: it exceeds the luminance headroom of OLEDs, and without mitigation, peak brightness can cause veiling luminance and visual discomfort.

Flicker/TLM: Due to the ultrafast recombination lifetime of inorganic LEDs, MicroLEDs can support very high-frequency PWM (>10 kHz) or true DC analog current driving. Thus, the design will be free from visible flicker. Active-matrix backplanes of LTPS or CMOS can integrate per-pixel current sources for stable driving and reduced modulation depth. Active-matrix MicroLED concept is shown in Fig.2.

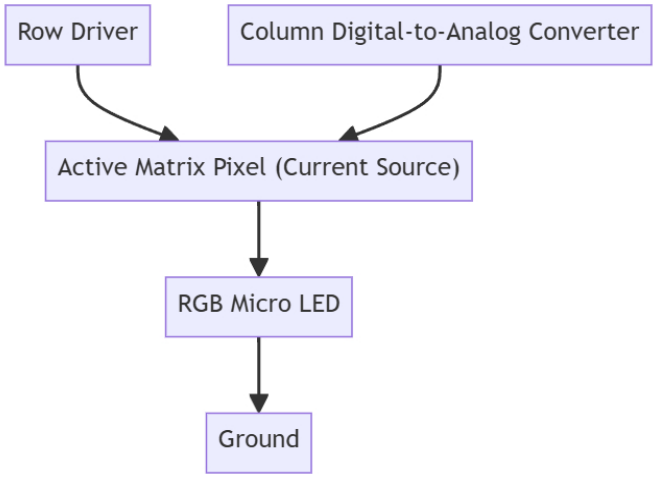

Fig. 2 Active-matrix MicroLED concept (Picture credit: Original)

Thus, MicroLED has the greatest intrinsic potential to balance high performance with low ocular stress, provided brightness management is handled responsibly.

3.4. Cross-technology summary

LCD, OLED and MicroLED have different ocular safety and comfort characteristics, and these are influenced by the driving electronics and spectral design choices, not just the display materials [10].

Blue-light: All three technologies can satisfy IEC 62471 RG0–RG1 under normal use, yet their SPDs differ. LCDs use phosphor-pumped blue LEDs with a strong 440-460 nm peak, and OLED and MicroLED can achieve more spectral tuning. Enable 'warm mode' or 'night mode' in practice to reduce melanopic and blue light hazard indices during the evening.

Flicker/TLM: Many OLEDs are PWM-dimmed, and sometimes the frequency is within the range of human perception. MicroLEDs' physics allow designers to easily exceed 10kHz PWM or work in DC mode and thus avoid TLM risks. According to IEEE 1789, a relatively high frequency and low modulation depth are needed for comfort; therefore, if the manufacturer follows best practices, MicroLED is a very flexible option.

Performance Trade-offs: OLED and MicroLED have higher native contrast and response speed, suitable for HDR and motion. Mini-LED local dimming has brought LCDs closer, and HDR TVs are now relatively common; however, LC switching speed remains a problem.

Practical Comfort Factors: Panel physics are only one part; other factors contributing to digital eye strain include ambient reflectance, UI design (font size and colour scheme), viewing behaviour (distance, duration, blink rate), etc. Therefore, the best hardware still needs all-encompassing system-level optimisation and user-friendly modes [11].

MicroLED generally has the highest potential for high-performance, eye-friendly technology, and at present, OLED is the most mature emissive option; LCD continues to lead in large-scale, cost-sensitive applications and has been steadily improving.

Table 1. Comparative Summary of LCD, OLED, and MicroLED Technologies

Feature	LCD (with Mini-LED Backlight)	OLED	MicroLED
Display Principle	Transmissive	Self-emissive	Self-emissive
Native Contrast	Good to Excellent (via local dimming)	Near-infinite	Near-infinite
Response Time	Millisecond-scale (ms)	Microsecond-scale (μs)	Nanosecond-scale (ns)
Peak Brightness	High to Very High (>2000 nits)	Medium to High (>1000 nits)	Extremely High (>10,000 nits)
Lifespan / Reliability	Very Good (inorganic materials)	Good (organic materials subject to degradation/burn-in risk)	Excellent (inorganic materials)
Primary Dimming Method	Backlight PWM / DC Dimming	Per-pixel PWM / DC Dimming	Per-pixel PWM / DC Dimming
Flicker Risk (TLM)	Medium to High (dependent on backlight PWM frequency)	Medium to High (dependent on low-brightness PWM frequency)	Very Low (easily supports ultra-high freq. PWM or DC dimming)
Blue-Light Hazard (SPD)	Dependent on blue LED + phosphor spectrum	Tunable spectrum	Tunable spectrum with highest potential
Circadian Impact	Medium, adjustable via software	Medium, adjustable via software	Low to Medium, strong capability for spectral control
Key Advantages	Mature technology, cost-effective, scalable to large sizes	Exceptional contrast, thin & light, flexible form factors	High brightness, long lifespan, high energy efficiency
Key Challenges	Slower response time, light leakage	Burn-in risk, blue subpixel lifetime	Mass transfer technology, manufacturing cost

4. Conclusion

Three representative display technologies, LCD, OLED and MicroLED, have been selected as the subjects of this study to compare their performance trade-offs and effects on the eyes. Based on the engineering principles of the above technologies and standardisation, such as IEC 62471 (blue-light hazard), IEEE 1789 (temporal light modulation) and CIE S026 (non-visual photoreception), an orderly system for evaluating display quality and human-factor risks has been constructed.

Mini-LED local dimming technology in LCDs can reduce the total backlight output to improve the contrast of HDR significantly and reduce the luminance burden to some extent. LCDs still have the basic problem of a slow liquid-crystal response time, and they are often driven by PWM-controlled LED backlights that may cause flicker at certain frequencies. A reasonable driver can be selected to reduce the frequency of PWM or use DC dimming.

OLEDs are self-emissive pixels that have high contrast and a fast response speed, so they are suitable for both consumers and professionals. The main health problems are related to PWM dimming at a low brightness and extended near-field viewing, which can cause digital eye strain. Software functions of night mode, spectral tuning and high-frequency PWM can address the above problems; however, sensitive users may still be bothered by flicker or temporal dithering.

MicroLEDs have combined the advantages of the previous two technologies to achieve high-brightness headroom, fast response, wide gamut and excellent durability. They are inorganic emitters that can reduce the blue-hazard index through spectral engineering, and active-matrix drivers can perform high-frequency PWM or true DC operation to virtually eliminate flicker. The main issue is the scale of production; otherwise, MicroLEDs would probably be one of the most popular user-friendly technologies.

In short, none of the displays are inherently harmful or safe; rather, the engineering choices of spectral tuning, driver circuits and brightness management affect eye comfort. In the future, hardware optimisation will be combined with system-level control to reduce digital eye strain by adjusting brightness and spectral filtering adaptively, etc. Good habits of the user are still necessary to reduce exposure to the blue light emitted by the device.

Therefore, LCDs will continue to be used for cost-sensitive large-format applications and OLEDs will remain popular in mobile phones; however, MicroLED is expected to set a new standard for high-performance, visually comfortable displays in the next generation.

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