ChatGPT

# Color Mapping for Liquid Light Visualization

- **Display Context:** Primarily on screens (standard sRGB/OLED).
- **Primary Use Case:** Both — low-fatigue ambient feedback with occasional high-contrast highlight events.
- **Accessibility Constraints:** Yes, include color-vision-deficiency considerations.

## Perceptual Uniformity in Color Mapping

A key goal is to ensure **perceptual uniformity** in the color palette so that equal changes in the underlying data or state correspond to equal perceived color differences. Using a non-uniform color space (like naive RGB or the old rainbow/"jet" colormap) can introduce abrupt visual contrasts that mislead the viewer into seeing false patterns or edges in the data [1] [2]. In other words, the human eye might interpret sudden hue jumps as significant changes when they are merely artifacts of the color scale. To avoid this, the palette should be designed in a **perceptually uniform color space** such as CIE Lab or its cylindrical variant CIE LCh (also known as HCL). These color models were explicitly developed to approximate human perceptual uniformity [3], meaning a given step in any direction in this space produces about the same perceived color difference. Many visualization experts prefer Lab/LCh for constructing color maps to eliminate distortion of the data patterns [1].

In practice, this means we will define our **Liquid Light** color gradients by linearly interpolating colors in LCh space (adjusting luminance *L* and chroma *C* gradually while perhaps shifting hue *h* if needed) so that transitions are smooth. A well-chosen sequential palette in LCh ensures no segment of the range is unintentionally salient or under-salient. Perceptual uniformity prevents visual "banding" or false contours; for example, the notorious rainbow palette often creates *apparent* sharp boundaries that do not exist in the underlying data [2]. By contrast, modern colormaps like **viridis** (a blue–green–yellow palette) were designed to be perceptually uniform and have largely replaced the flawed rainbow scales [4]. We will take a similar approach, using a uniform color progression so that *liquid light* variations are represented faithfully without unintended visual artifacts.

*Moreover, working in Lab/LCh gives us direct control over luminance, which is important for maintaining consistent contrast.* For display on standard sRGB/OLED screens, we must also ensure the chosen colors remain **in-gamut** for sRGB. (Lab/LCh spaces are device-independent and can define colors humans can see but which might be outside a typical monitor's range. We will constrain our palette to colors that sRGB devices can actually reproduce [5].) In summary, the palette should be crafted in a perceptual color space and then mapped into sRGB, guaranteeing that what users see on their screen is both accurate and uniformly scaled to the eye.

## Palette Design for Ambient and Highlight Uses

**Ambient low-fatigue visualization:** For the continuous, ambient feedback mode, the palette will favor **soft, low-saturation colors** with moderate brightness. Research in color ergonomics shows that extremely bright, saturated colors can overstimulate the eyes and cause fatigue [6]. In fact, pure bright lemon yellow is cited as particularly fatiguing because it reflects so much light (leading to excessive retinal stimulation) [6]. To keep the display comfortable over long periods, the base palette should avoid such extremes. Instead, we propose using a calm range of hues (for example, a **blue-green "liquid" gradient** or a cooler teal/cyan range) at relatively low to medium chroma. Blues and blue-greens are often perceived as soothing and, importantly, a sequence of bluish tones with varied lightness can be made nearly isoluminant or smoothly varying, producing a gentle background shift. As long as the luminance differences are kept subtle and the colors are not neon-bright, this will create a **low-fatigue** backdrop. (*Note:* If a blue-toned palette is used in a dim environment, we may later adjust its spectral content for nighttime as discussed in the safety section.)

In LCh terms, one could hold hue roughly constant (e.g. around a teal-blue hue angle) and vary luminance for the ambient effect – this yields a series of shades from darker to lighter teal that are perceptually evenly spaced. Such a **sequential palette** ensures a smooth gradient for any "liquid light" animation or data mapping, without jarring jumps. The chroma (color intensity) can be kept moderate; very high chroma is not only tiring but can also shift perceived lightness non-uniformly. A controlled chroma also tends to appear more **transparent** or subtle, fitting an ambient display.

**High-contrast highlight events:** In addition to the base gentle palette, we need an **accent color** (or a small set of accent colors) for occasional important events or alerts. These highlight colors should be **sharply distinct** from the ambient colors to attract immediate attention, fulfilling an alert function. Color science indicates that the human eye is drawn to high luminance contrast and to certain hues like yellow first [7]. We can leverage this by choosing a highlight color that contrasts in both hue and brightness against the ambient scheme. For instance, if the ambient palette is blue/teal, a warm **amber or orange** highlight will stand out strongly. Blue versus orange is a well-known effective pairing: not only are they opposite in hue (enhancing contrast), but such a combination also tends to remain distinguishable under various forms of color vision deficiency [8]. **Blue and orange** (or blue and a yellow-green) viewed by a red-blind individual might appear as blue and olive, and to a green-blind viewer as blue and a distinct orange – in all cases the pair remains distinct [8]. This makes a blue–orange pairing both attention-grabbing for normal vision and still recognizable for color-impaired viewers. We will therefore select a highlight color like a golden yellow or orange at a high brightness and saturation for maximum salience. It should be used sparingly – for example, a brief pulse or a single element – because large areas of very saturated color can be glaring. Used in moderation, a highly saturated warm highlight on a cool, subdued background provides an excellent **signal-to-noise ratio** for critical events.

To summarize the proposed palette system: a **base gradient** of perceptually uniform, mild colors (likely in the blue/cyan family for a "liquid light" feel, though greens or violets could also be considered with similar uniformity constraints) for continuous display, and a **complementary accent** (such as an orange/yellow or magenta, depending on final aesthetic) reserved for transient highlights. All colors will be chosen via LCh space calculations to ensure uniform steps and then converted to sRGB for display. The overall luminance range of the ambient palette will be limited to avoid eye strain, with the highlight color peaking higher in luminance and/or saturation only during momentary events. This approach guarantees that under normal viewing the interface remains gentle, but when attention must be drawn, the contrast is sufficient and immediate.

## Accessibility for Color Vision Deficiency (CVD)

Designing with **color vision deficiencies** in mind is a strict requirement. A significant portion of the population has some form of CVD – on the order of **~8% of males** (and around 0.5% of females) have reduced ability to distinguish certain colors [9]. Failing to account for this means those users could misinterpret or completely miss critical information in the visualization. Therefore, the palette system will be crafted to be **colorblind-friendly**. Here are the strategies we will apply:

- **Avoid Problematic Color Combos:** The most common CVD types (protanopia and deuteranopia) affect red/green sensitivity, so a classic rule is to avoid conveying information by **red vs green** alone [10]. Combinations of reds, oranges, browns, and greens can collapse into indistinguishable shades for a red-green colorblind viewer [10]. In our context, this means we should not use a greenish ambient and a red highlight (or vice versa) as the sole differentiator, since a protanopic user might see both as a similar mud tone. Likewise, other confusing pairs (like turquoise vs pink, or purple vs blue) will be avoided unless we ensure additional differences in lightness or saturation to tell them apart [11].

- **Leverage Lightness Differences:** A robust principle is to encode differences not just in hue but also in **luminance (lightness)**, because even someone with no color vision at all (monochromacy) or when viewed in grayscale, differences in lightness remain perceivable [12]. We will ensure that our ambient palette spans a range of lightness values that are distinguishable in grayscale. For example, the darkest teal vs the lightest teal in our background gradient should differ clearly in brightness so that even if the hue information is lost, one can discern a change. Similarly, the highlight color will not only differ by hue but also be significantly lighter or darker than the background at the moment of highlight, providing a contrast in brightness that pops out. Designing the palette in LCh makes this straightforward since L (luminance) can be managed directly. *Using varying lightness is even a fallback if a traditionally problematic hue must be used:* research notes that even a red-green pair can be made distinguishable to CVD viewers by giving them a strong lightness contrast [12].

- **Test with Simulators and Tools:** We will validate the palette with tools like **Viz Palette** or **Color Oracle** that simulate color blindness [13] [14]. These tools highlight if any two colors in the scheme become too similar under protanopia/deuteranopia/etc. During design, if we find any ambiguities (e.g., two distinct states in the visualization appearing identical to deuteranopic observers), we will adjust the colors accordingly. The use of a blue-cyan base and orange accent, as proposed, is already a known good practice for accessibility, since blue/orange remains a contrasting pair across all common CVD types [8]. Still, fine-tuning will be done (for instance, ensuring our chosen orange isn't so dark that it looks brown against a grayish background to certain users, etc.).

- **Limit Palette Size if Categorical:** If the visualization ever uses multiple distinct category colors (beyond the one accent), we will limit the number of simultaneous colors to what can be reliably distinguished. Studies have found that truly colorblind-safe **categorical palettes** with more than about 4–5 colors are rare [15]. It's better to use additional cues (shapes, patterns) for more categories than to force many colors that will inevitably include unsafe pairings. In our case, since the primary use is a continuous ambient scale plus one highlight, we are within safe limits – essentially two predominant hues. Any additional status indicators will follow the same rules (for example, if a second highlight color is needed, we might choose a magenta or cyan that remains distinct from both the base and the first accent, checking it in simulations).

By implementing these measures, the **Liquid Light Visualization** will be inclusive. A user with color blindness should be able to perceive the ambient changes (via lightness cues if not hue) and detect highlight events without confusion. All critical distinctions will have redundant visual encodings, not solely reliant on color hue. This adherence to accessibility is not just ethical but often improves overall clarity for all users.

## Photobiological Safety and Visual Comfort

Beyond perceptual accuracy and accessibility, we impose **safety constraints** related to human physiology – essentially making sure the visualization is easy on the eyes in a literal, biological sense. This covers managing blue light exposure, brightness levels, and any flashing patterns:

- **Circadian-Friendly Color Choices:** Since the display may be viewed in ambient, potentially low-light conditions, we consider the impact of color on viewers' **circadian rhythms** and comfort. Scientific findings show that exposure to **blue light** (around 400–490 nm) at night suppresses melatonin, making it harder to fall asleep [16]. Blue wavelengths also strongly stimulate the intrinsically photosensitive retinal cells, which can disrupt the body's clock. Our palette will therefore include a strategy for **night mode or warm-toned adjustment** during evening hours. While the base "liquid" palette might skew towards cooler colors for aesthetic reasons, we can slightly shift it to the greener or more turquoise side (reducing pure-blue intensity) or reduce overall brightness at night. The **NIOSH/CDC** guidance indicates red or dim amber light has minimal effect on the circadian clock [17], whereas blue/white light has the strongest impact. We likely won't make the entire interface red at night (as that would change the design drastically), but we will ensure no large bright blue areas are on a dark screen for long periods. A **dimmer, warmer tint** for the ambient glow in dark conditions can achieve low fatigue. In daytime or alert scenarios, more blue content is acceptable (blue light in daytime can boost alertness and mood [18]), but user comfort in various environments will be kept in mind.

- **Blue Light Hazard and Intensity:** Modern LED/OLED screens emit a lot of blue light, and there is ongoing research about the **photochemical risks to the retina** from chronic exposure. Blue wavelengths carry more energy and prolonged viewing at high intensity could contribute to retinal stress or macular degeneration risk [19]. While our use case is not as extreme as staring into an LED lamp, it's important to **minimize excessively bright, saturated blue** in the design. We will cap the maximum brightness (luminance) of the palette to a safe level – no all-white flash or fully saturated blue fullscreen moments. The highlight events, if they involve a bright color (like a flash of yellow/white), will be brief and as small-area as possible. A review on LED blue light notes that exposure to intense blue can induce photoreceptor damage, urging mindful spectral design of lighting [20]. Thus, our highlight flashes will likely lean toward a warmer white or yellow (which has a broader spectrum) rather than a pure blue flash. In short, **no single element of the visualization will approach unsafe brightness or remain glaringly on**: the design goal of "low-fatigue ambient" inherently means moderating intensity to avoid eye strain.

- **Avoiding Flicker and Flashing Risks:** For any dynamic highlight (for example, a pulsing alert or blinking indicator), we will abide by the well-established safety guideline of **flash frequency**. Flashing content can trigger photosensitive seizures in a small percentage of viewers if it's in the dangerous frequency range roughly **3–30 Hz**. To be safe, we will ensure that any blinking highlight **does not exceed 2–3 flashes per second**, and ideally use slower gentle pulses or a smooth fade-in/

out rather than hard blink transitions. According to accessibility standards (e.g., W3C's Web Content Accessibility Guidelines), content should not flash more than three times in one second [21]. Furthermore, higher contrast flashes against a dark background are more provocative, so if a highlight must blink, we may slightly reduce its peak brightness in a dark room scenario to mitigate risk [22]. Our design can likely avoid rapid flashing entirely (perhaps using a color change or motion as an alert instead of flicker), but if used, it will be within safe limits to **not induce headaches or worse**.

- **General Visual Comfort:** Lastly, we take general **eye comfort** into account. The palette's colors will be chosen not only for data reasons but also considering known effects like afterimages and focus strain. For example, staring at a large field of pure red or pure blue can fatigue specific cone cells and lead to after-image illusions (seeing a complementary color ghost) [23]. We mitigate this by using **softer tones and avoiding large solid areas of any extremely saturated color**. If the visualization's background is a solid color, it will be a dark or muted shade (not a blinding white, and not an intense pure hue). Contrast polarity is also a factor: big jumps from dark to light (like black text on pure white or vice versa) cause the eye to continually refocus and can be tiring [24]. Our ambient gradients will likely be middle-value colors on average (neither very dark nor very light extremes), providing a gentle contrast that does not overstress the eyes. Essentially, the design aligns with the principle that **"the appropriate use of color can maximize productivity and minimize visual fatigue"** [25]. By using color as guided by human factors research – e.g., small amounts of vivid color to draw attention, and large areas of subdued color for comfort – we ensure the visualization remains **visually safe** for continuous use.

## Conclusion

In this **"Color Mapping for Liquid Light Visualization"** memo, we outlined a palette system that balances aesthetic and functional needs with perceptual and physiological safety. The proposed approach leverages **CIE LCh color space** to achieve perceptual uniformity, ensuring that the visualization's fluid color changes accurately represent underlying changes without introducing false visual cues [1]. We have planned a **two-tier palette**: a gentle, **low-fatigue ambient gradient** (likely in cool hues) and a **high-contrast accent** color for highlight events. The choices are vetted for **accessibility**, using colorblind-safe strategies so that no user is left confused – for example, avoiding red-green contrasts and embedding adequate lightness differences for visibility in grayscale [12] [10]. Furthermore, we introduced **safety constraints** from photobiology: limiting blue light exposure in dark settings [16], avoiding dangerously bright or flickering visuals, and generally conforming to what is known about eye comfort and health [20] [6].

By citing proven research and guidelines, we ensure that this color mapping not only looks appealing and coherent but is also *trustworthy* from a human-centric design perspective. Users will be able to engage with the Liquid Light Visualization for extended periods without undue eye strain, and all critical information conveyed through color will remain discernible to as wide an audience as possible. This palette system exemplifies an evidence-based design: marrying the art of color choice with the science of human perception and well-being.

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