Real High Contrast or Only Marketing Hype?
Color Resolution Factor Quantifies the Color Contrast of Any Lens.

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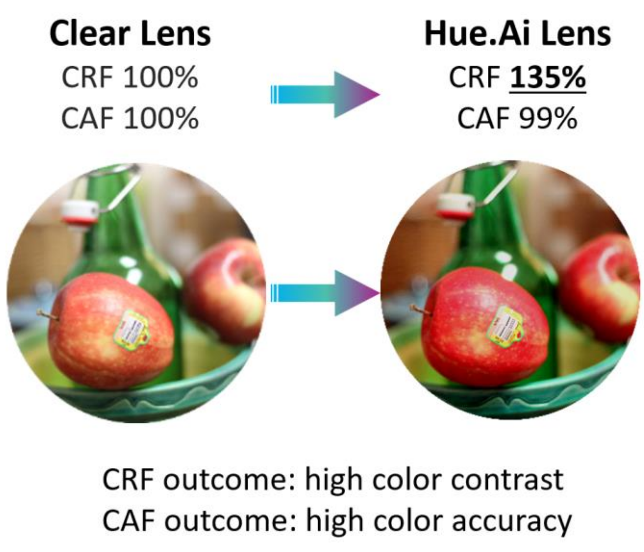
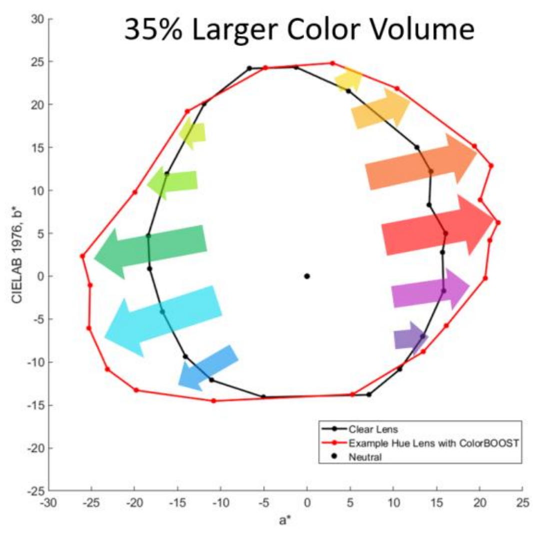
<u>Executive Summary</u>

This paper addresses the lack of practical and meaningful metrics to evaluate color contrast in optical and sun lenses, including contact lenses. We develop the quantifiable metrics of Color Resolution Factor (CRF) and Color Accuracy Factor (CAF) as tools for consumers and manufacturers to objectively assess the color contrast of any lens. The roots of these two metrics lie in the high-definition television (HDTV) industry. This industry depends on the demonstratable product outcomes of color contrast and resolution. It has spent billions of dollars in the perennial search for technologies that can display an ever-wider range of colors with greater accuracy and higher resolution.

Just as better TVs enhance viewing pleasure, “Color Contrast” or “Color Enhancing” optical lenses improve people’s visual experience and performance. In sports eyewear, high color contrast boosts visual awareness, target recognition, target tracking, and reaction time. In occupational eyewear products, it improves a user’s ability to detect safety markers, hazards, and anomalies. For lifestyle eyewear products, high contrast enhances the visual experience and cinematic feel.

Leveraging concepts originally developed for high-definition TVs, we propose that the optical industry should use CRF and CAF to evaluate the amount of color contrast of a lens. <u>CRF is the primary color contrast metric</u>, as it quantifies the number of distinguishable colors transmitted, which originate from optically-resolved visual details. A lens with a CRF >120% has demonstratable high color contrast, with a clear lens having a lower threshold. The CAF of a lens measures the <u>accuracy</u> of colors transmitted, with the maximum CAF value of 100% being that of a perfectly clear lens. The two metrics present a verifiable and accessible way to meaningfully evaluate color contrast lenses.





The above two figures compare the color contrast of an example Hue.Ai patented ColorBoost lens (red line), relative to a clear lens (black line). The example Hue.Ai lens has a 35% higher color contrast as evidenced by the vivid photo, a CRF of 135% and a 35% larger color volume. A CAF of 99% shows our lens preserves color accuracy, ensures depth perception, and promotes visual comfort. <u>Hue.Ai’s high color contrast lenses have demonstrably high color resolutions and high color accuracies.</u>

Why Measuring Color Contrast Is Important

Improved “color contrast” or “color enhancement” are terms commonly used in the eyewear industry to advertise lenses that claim to increase color perception for performance and enjoyment. However, today these claims are not defined nor quantified, leaving uninformed wearers resorting to their own unguided interpretations and imaginations. This chasm between the advertised contrast improvement and actual visual experience is well-known in the eyewear industry.

Key performance indicators related to visual awareness, recognition, depth perception and reaction are all based on binocular color vision. Lenses with actual high color contrast aid wearers by improving their performance, such as in sports, occupations, safety, and military applications. A color contrasting lens also makes colors more vibrant for the enjoyment of life experiences, such as hiking in the forest, or strolling through a rose garden (“visual environment”). However, current lens performance and quality criteria that are only dependent on black-white contrast, such as optical resolution, may have been sufficient prior to 2010s, but they are insufficient in the modern world of color we live in today.

<u>The eyewear industry should adopt quantitative metrics on color contrast</u>, just as data on UV-blocking and transmittance (VLT) are industry standards of today. Toward this end, this white paper offers definitions and metrics to evaluate lenses on their ability to improve color contrast. We propose metrics adapted from the modern display industry for use in the optical industry.

Background and Adaptation of Color Contrast Metrics from Displays to Lenses

In recent years, televisions have advanced from “standard definition” to “High Definition”, and to “4K”, often now with “HDR” (high dynamic range). Consumers readily compare improvements in picture quality by using published color and contrast metrics. The color display and television industries benchmark the color performance of their products using the metrics of color volume (or color gamut) and color depth (or color bits). Color volume of a display quantifies the range of colors it can produce. The color depth of a display evaluates the number of distinguishable colors producible per pixel. Finally, the color resolution of a display evaluates the number of distinguishable colors producible per linear distance of the display, e.g., per inch. Therefore, color resolution equals color depth multiplied by the display’s pixel density, e.g., pixels per inch (PPI). Color resolution is preferred over color depth as a standard distance is easier to measure than a pixel.

We propose that color resolution is the primary framework to evaluate color contrast. We accomplish this by adapting color resolution of a digital display to that of a lens. A pixel is equivalent to the optical resolution of a lens. The smallest displayable element is exactly the same principle as the smallest optically-resolved distance of a lens. Therefore, the pixel density of a display is equivalent to the Spatial Cutoff Frequency (SCF) of a lens—an industry standard measure of a lens’ optical resolution. SCF is often measured in line-pairs per millimeter (lp/mm), like pixel density’s PPI. For example, an average well-made polymer lens has a SCF of 30 lp/mm. Building upon these principles, we adapt the foundational concepts of color volume, color depth and color resolution of a color display to those of a lens.

(1) Colors come from a visual environment and are then transmitted through a lens.

(2) A visual environment is composed of optically-resolved visual details.

(3) The <u>color volume of a lens</u> measures the range of colors. The <u>Color Volume Factor (CVF)</u> is the color volume of a contrast lens relative to that of a clear lens.

(4) The <u>color depth of a lens</u> measures the number of visually distinguishable colors in the optically-resolved visual details of the smallest size (i.e., “per pixel”).

(5) The <u>color resolution of a lens</u> quantifies the <u>perception</u> of the number of visually distinguishable colors in the optically-resolved visual details of the standard size (e.g., per millimeter). The <u>Color Resolution Factor (CRF)</u> is the color resolution of a contrast lens relative to that of a clear lens.

<u>CRF is the primary metric to assess the color contrast of a lens.</u> Colloquially, a lens’ color volume measures the amount of color saturation perceivable through the lens. A lens’ color depth measures the number of colors perceivable through the lens, “per pixel” of the visual environment. A lens’ color resolution improves upon color depth by aggregating over a larger, standard distance in the visual environment, instead of a “pixel”. In the next section, we show color resolution is fundamental to understanding and calculating color contrast. Color resolution is derived from color depth and traditional black/white optical resolution of a lens. Moreover, color depth is derived from color volume. Therefore, color resolution is also a function of color volume. This means <u>a lens with higher color resolution transmits higher color saturation, and more shades and hues of colors in the optically-resolved visual details of the standard size.</u> These are hallmarks of a lens with high color contrast that transmit many visually distinguishable colors.

An average visual environment, such as urban and suburban settings, contain a balanced set of warm, cool, and neutral colors. This type of environment may be called an “everyday” environment. Other visual environments, such as snow, desert, ocean, and forest, contain colors skewed towards the warm, cool, or neutral colors. Hue.Ai’s ColorBoost lenses are tailorable to a particular visual environment to enhance or maximize visual performance or experience.

Color Accuracy Factor (CAF) is a secondary color contrast metric we adapt from the display industry, that assesses the balance of warm, cool, and neutral colors in the color volume of a lens. Often a lens is tinted a particular color to accentuate its analogous colors. A lens’ tint (“white point”) skews the entire color volume seen through the lens towards its white point. For example, an orange tinted lens accentuates warm colors. However, the negative side effect of a strong lens tint is the diminishment of opposite colors, such as cool colors in the case of an orange tint. A strong tint can also shift neutral colors, e.g., whites and greys, which can cause visual discomfort and fatigue.

<u>Color Resolution Factor Is the Primary Metric to Evaluate Color Contrast</u>

Color contrast of a lens should include and further expand upon its black/white contrast. In traditional optics, black/white contrast measures the optical resolution of a lens. Therefore, color contrast of a lens must also incorporate optical resolution as a component. Moreover, the color contrast between two colors is their distinguishable color difference. Here, we introduce the important concept of <u>distinguishable perception</u>: a person can only see two colors being different if their color difference is larger than the psychophysical threshold called Just Noticeable Difference (“JND”). JND is central to understanding that a person only sees a finite number of intermediate colors between two colors. Therefore, said in an equivalent way, the color contrast between two colors is measured by the number of perceptually distinguishable colors that intermediate between the two colors.

The color resolution of a lens incorporates both perpetually distinguishable colors and optical resolution—hallmarks of color contrast. Hence, <u>we propose color resolution as the primary framework to understand and measure color contrast</u>. Since color resolution can take on any positive value, it is more useful to define the color resolution of any lens relative to that of an idealized clear lens with

100% transmission of visible light. We define Color Resolution Factor (CRF) as such relative color resolution of a lens.

$$Color\ Resolution\ Factor_{Contrast\ Lens} = \frac{Color\ Resolution_{Contrast\ Lens}}{Color\ Resolution_{Clear\ Lens}} * 100\%$$

Equation 1.

CRF is the color contrast seen through a spectrally tuned, contrast lens relative to a clear lens. A CRF of 100% indicates that there is zero net change in the perceived color resolution. A CRF of >100% indicates a net gain, and a CRF of <100% indicates a net loss in the perceived color resolution. From our field tests, a CRF of approximately 120% is the threshold for a person to definitively perceive higher color contrast, including more shades and hues of colors and higher saturation of colors, in the optically-resolved visual details. A clear lens requires a lower CRF threshold due to the Hunt Effect. For an example Hue.Ai lens with our ColorBoost technology currently in the market, it has a **CRF of 138%**. This high CRF value indicates that the Hue.Ai Lens enables a person to see 38% more color resolution, i.e., 38% more optically-resolved color contrast, relative to a clear lens. We show how to calculate the CRF in the rest of this paper.

Figure 1 shows the one visual environment seen through a lens with a low CRF of 80% (left), a standard CRF of 100% (middle) and a high CRF of 138% (right). These images clearly show that a high CRF has a larger color volume, a higher color depth and a higher optical resolution. The larger color volume is indicated by more saturated colors and a larger color range. The higher color depth is exemplified by more shades of colors. The higher optical resolution is seen in the better-resolved, sharper details of the image.

Color banding, an undesirable phenomenon, is also clearly visible in the low CRF scene. Another example of a visual environment with typically low CRF and exhibits color banding is golfing on a grass fairway. A golfer wearing a pair of Hue.Ai lenses with a high CRF value would see much more color contrast in the grass, which helps the golfer to “read the greens”.

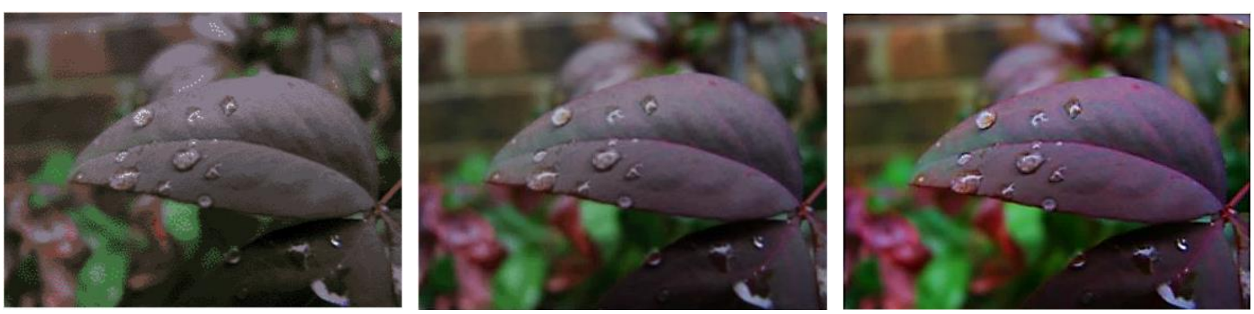


Figure 1. A visual environment with a low CRF of 80% (left), a standard CRF of 100% (middle) and a high CRF of 138% (right). Courtesy of Wikipedia.org

<u>Color Resolution Factor Is Based on Color Depth and Spatial Cutoff Frequency</u>

A high CRF is the primary performance indictor of a lens that improves color contrast. To calculate CRF, we need to better understand color resolution and derive it from baser metrics. As explained in the Background section, color resolution is a function of color depth and the SCF of a lens. Later in this paper, we also show color depth is a function of color volume. Therefore, a <u>lens with higher color resolution is able to transmit more saturated colors, and more shades and hues of colors that come from the standard-sized optically-resolved details in a visual environment</u>. Equation 2 shows the dependency of color resolution.

$$Color\ Resolution_{Lens} = function(Color\ Depth_{Lens}, Spatial\ Cutoff\ Frequency_{Lens})$$
Equation 2.

"Per pixel" of the visual environment, color depth measures the number of visually distinguishable colors that come from a visual environment and are then transmitted through the lens. Therefore, the key to calculate color depth is to calculate the number of visually distinguishable colors in a visual environment. Consequently, we need to understand the minimum threshold of distinguishable color difference. Color banding, shown in Figure 2, is a common phenomenon in digital displays, photography, and printing where color differences within a band are imperceivable, and only colors from different bands are perceivable. The number of distinguishable colors is equal to color volume divided by the average size of color bands. In Figure 2, for the color volume containing reds and black, there are 6 distinguishable colors. Therefore, its color depth is 6 colors.

Figure 2. Just Noticeable Difference as illustrated by color banding. Color depth is 6 colors. Courtesy of Wikipedia.org

Equivalently, color banding exists in human color vision and is called Just Noticeable Difference (JND). In the standard 1976 CIE L*a*b* color appearance model, the JND is 2.0 linear units and 3.0 area units for an average person. Relationally, color depth is equal to color volume divided by JND. Shown in Equation 3, color depth of a lens is equal to the color volume, projected onto the a*b* plane, divided by JND.

$$Color\ Depth_{Lens} = \frac{Color\ Volume_{a^*b^*Plane\ Projected\ Area,\ \ Lens}}{Just\ Noticeable\ Difference_{Area}}$$
Equation 3.

Besides color depth, we also need to determine the SCF of the lens to evaluate color resolution. It is well-known that the optical resolution of a lens is evaluated by looking through the lens at the spatial frequency chart shown in Figure 3.

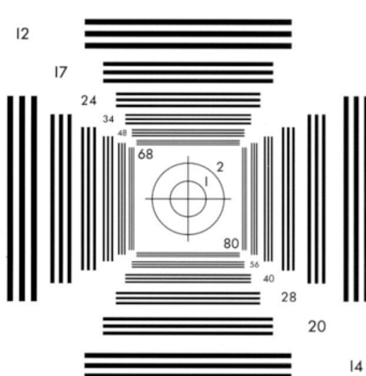


Figure 3. An optical resolution chart showing various spatial cutoff frequencies.

The SCF is the number of line pairs per millimeter corresponding to the set of black/white bars that looks marginally separated to the average person. The greater the SCF, the higher the optical resolution. As a high-resolution digital display has a high pixel density, a high-quality polymer lens has an average optical resolution of 30 lp/mm, which we use as the reference value. Mineral lenses can achieve an optical resolution of 40 lp/mm. A high SCF is due to several factors, including well-polished surfaces and noncrystalline material structures.

Appendix A contains field data and detailed mathematical formulations of CRF as a function of both color depth and SCF, where color depth is also a function of color volume and JND. To conclude this section, we state the result of CRF formulation:

$$CRF = CVF * Relative\ SCF^{\frac{1}{6}}$$

Equation 4.

where CVF is the Color Volume Factor (explained in the subsequent section), and the relative SCF is the ratio of $SCF_{Contrast\ Lens}$ to the reference $SCF_{Clear\ Lens}$. The 1/6 exponent is a parameter calibrated to match Hue.Ai's field data on an average person's visual perception of the influence of the relative SCF on CRF. See Appendix A for details.

From Equation 4, we see the CVF of a lens has a dominant impact on its CRF, while the lens' optical resolution (measured via SCF) has a noticeable, but minor impact. Notably, a tuned transmission spectrum of a lens is the principal way to increase CVF and is therefore the primary way to increase CRF. Hue.Ai's patented ColorBoost technology optimizes the transmission spectra of (1) performance lenses to maximize CRF for function, and (2) lifestyle lenses to increase CRF for a cinematic visual experience.

Color Volume Factor Is a Primary Contributor to CRF

The color volume of a lens measures the range (or gamut) of colors that come from a visual environment and are then transmitted through the lens. CVF measures the size of the color volume of a spectrally-tuned, contrast lens, relative to that of an idealized clear lens. A lens with a high CVF transmits an enlarged color volume, enabling a person to see a wider range of colors in the same visual environment, including higher saturation of colors, relative to a clear lens. However, unlike the CRF, the CVF does not include an optical resolution component, i.e., is independent of SCF. In fact, a higher clarity lens and a lower clarity lens would have identical, high CVF values if they have identical transmission spectra that enlarge color volume and increase color saturation equally. But the higher clarity lens would have a higher CRF as its optical resolution is higher, enabling a person to see more color contrast in the optically-resolved details in the visual environment.

Formally, CVF quantifies the relative size of a lens's color volume, projected onto the 2-dimensional a*b* plane of the 1976 CIE L*a*b* color space. Mathematically, CVF is calculated as the percentage ratio of the projected area of the new color volume seen through a contrast lens to the projected area of the original color volume seen through a clear lens. Note, the visual environment itself does not change. Equation 5 describes CVF.

$$Color\ Volume\ Factor = \frac{Color\ Volume_{a^*b^*Projected\ Area,Contrast\ Lens}}{Color\ Volume_{a^*b^*Projected\ Area,Clear\ Lens}} * 100\%$$

Equation 5.

For the example Hue.Ai lens with ColorBoost technology having a CRF of 138% and a SCF of 34 lp/mm, its **CVF is 135%**. This high CVF value indicates that the Hue.Ai lens enables a person to see 35% larger color range, e.g., 35% higher color saturation, relative to a clear lens. A CVF of 100% indicates zero net change in the color volume. A CVF of >100% indicates a net gain, and a CVF of <100% indicates a net loss in the color volume. In our experience, a CVF of approximately 120% is the threshold for a person to definitively perceive a larger color range with more saturated colors. A clear lens requires a lower CVF threshold due to the Hunt Effect.

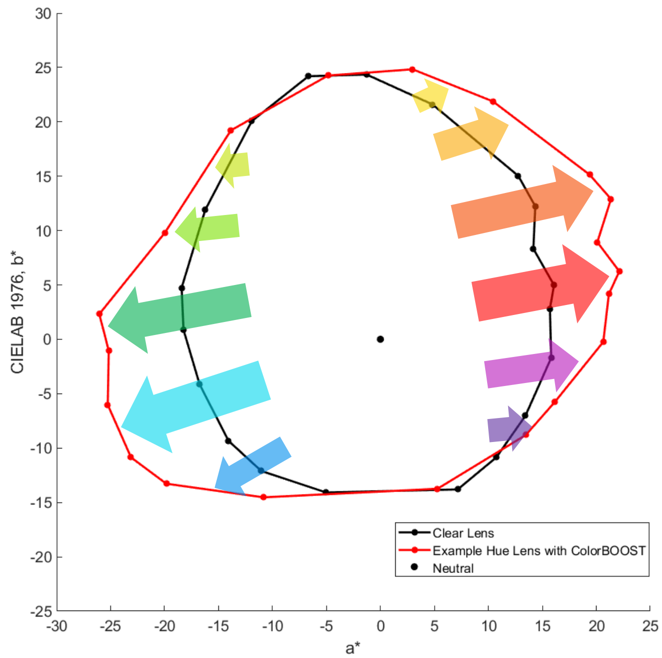


Figure 4. The Standard Color Volume seen through a reference clear lens (black) and seen through an example Hue.Ai lens having the patented ColorBoost technology (red), projected onto a*b* plane. The Hue.Ai lens enlarges the encircled area of the SCV by 35%, making its CVF equal to 135%.

Figure 4 shows the Standard Color Volume (SCV) seen through a clear lens (black line) and seen through an example Hue.Ai lens having a CVF of 135% (red line). The SCV is modeled in the 1976 CIE L*a*b* color space and is projected onto the a*b* plane. A set of 20 medium chroma Munsell colors[1], substantially selected from the well-known Farnsworth-Munsell 100 Hue Color Vision Test, encircles the SCV. As Figure 5 shows, these 20 colors represent common colors in an average visual environment by having a balanced and regular sampling of red, orange, yellow, chartreuse, green, cyan, blue, and purple hues. <u>We note that for certain visual environments, such as snowboarding and fishing, specific colors forming application-oriented color volumes may be desirable.</u>

Figure 4 shows an enlarged color volume is a key indicator of any lens claiming to improve color contrast. Analogously in the color display industry, a wide color gamut is a seminal characteristic of a state-of-the-art HDR TV. Figure 4 further shows all hues of the color volume have been expanded, i.e., increased in chroma/saturation. It is also important to note that the colors in the enlarged SCV largely maintained their original hues—preserving the original balance of warm and cool colors. A balanced color volume reduces visual discomfort and improves depth perception (see Color Accuracy Factor). Note that these computed color contrast outcomes are confirmed with the color perception data we measured from human testers.

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[1] Munsell colors are a type of standard color samples in color science. They are widely used in many industries, including US Geological Survey, US Dept. of Agriculture, lighting, photography, imaging, printing, ANSI forensic pathology, dentistry, and beverage.

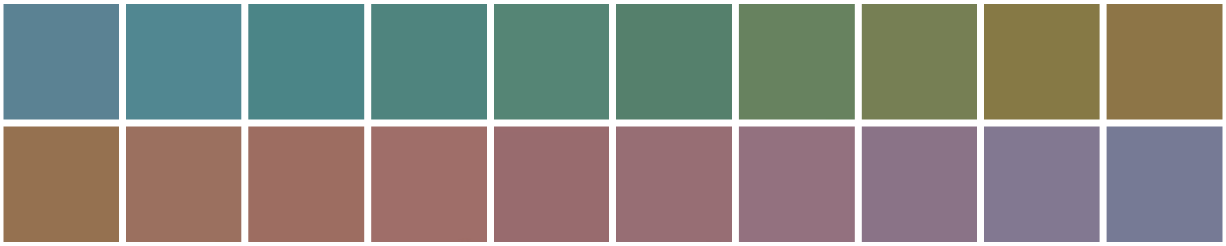

Figure 5. Twenty Munsell colors form the perimeter of the Standard Color Volume.

To compute CVF, we need to first evaluate the color volume of a lens. To do so, the process uses color science, 20 Munsell colors, a tuned transmission spectrum of a lens and a light source. We recommend readers interested in the computation to see Appendix B.

Figure 6 is a diagram showing the needed components and process to calculate the CRF and CVF of a lens. The primary approach for a lens maker to increase color contrast of lens, via increasing CRF and CVF, is to modify its transmission spectrum.

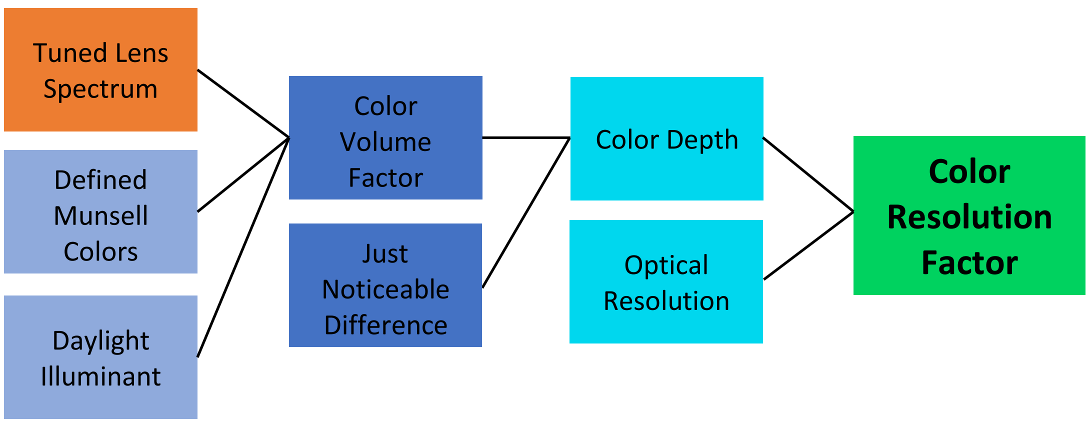

Figure 6. Process to calculate Color Resolution Factor and Color Volume Factor of a lens.

<u>Color Accuracy Factor Measures the Accuracy of Colors Transmitted</u>

The Color Accuracy Factor (CAF) is a metric to quantify the accuracy of colors transmitted through a contrast lens, relative to a clear lens. CAF has a maximum value of 100% for the clear lens. A colored lens tint has a lower CAF. A lens with a high CAF better preserves depth perception as it better preserves color and shadow cues used in depth perception. Traditionally, a colored lens is a tool to accentuate analogous colors while diminishing their opponent colors by shifting the entire color volume. For example, a red lens will accentuate warm colors while diminishing cool colors by shifting the entire color volume seen through the lens towards red. This type of traditional color contrast technology lowers CAF. In contrast, Hue.Ai's new ColorBoost technology can selectively accentuate target colors without sacrificing their opponent colors, while keeping a neutral or pastel lens tint. Our ColorBoost lenses can also accentuate both target and opponent colors simultaneously! Our new color contrasting lenses increase CRF and CVF with little to no tradeoffs in CAF. Equation 6 defines the CAF.

$$Color\ Accuracy\ Factor = \frac{100\%}{1 + 0.0101 * e^{0.1072 * Chroma_{Lens\ White\ Point}}} + 1\%$$

Equation 6.

A CAF of at least 95% indicates high color accuracy, comparable to seeing colors through a perfectly clear lens. A CAF of less than 90% indicates colors seen through the lens are skewed towards the lens' color. A CAF of less than 80% indicates a lens that significantly skews colors. For the example Hue.Ai lens with a CRF of 138%, its CAF is 99%. This Hue.Ai lens has a color resolution 38% higher than that of a clear lens and a color accuracy substantially equal to that of a clear lens—hallmarks of a lens with superior color contrast and color accuracy.

Conclusion

The television industry has spent billions of dollars in product development and marketing over the decades to fuel the global competitive race for better color images. Countless scientists and engineers dedicated their careers to the perennial search for technologies that can display an ever-wider range of colors, accurately and with ever higher resolution. Adapted from the display industry, we propose measuring the color contrast of a lens using the two metrics of CRF and CAF, with CRF being the primary metric. The color resolution of a lens quantifies the perception of the number of visually distinguishable colors that come from the optically-resolved visual details of the standard size (e.g., per millimeter). Equivalently, an increase in the number of visually distinguishable colors exactly translates to the same increase in the saturation of colors—a hallmark of color contrast. CRF is the color resolution of a contrast lens relative to that of a clear lens. CAF measures the accuracy of colors seen through a lens. High CRF and CAF values indicate a high color contrast, color-accurate lens.

In sports eyewear products, a high CRF lens enhances visual awareness, target recognition, target tracking, and reaction time. An occupational eyewear product with high CRF lenses increase the user's ability to detect job-critical objects, safety markers, hazards, and anomalies. For lifestyle eyewear products, a high CRF lens improves the visual experience and cinematic mood generally. In each of these categories, CAF is a further indicator of high color quality, as high color accuracy balances warm/cool colors, preserves depth perception, and promotes visual comfort.

We propose these two metrics of CRF and CAF to assess and differentiate real color contrast lenses from the marketing hype. Quantitative metrics yield meaningful ways for consumers and eyewear brands to compare high contrast lens options for their visual goals. We believe the industry would greatly benefit from using these published and useful metrics of color contrast.

About Hue.Ai and the Author

Hue.Ai is an American technology company focused on using Generative Artificial Intelligence and proprietary materials to develop and bring to market state-of-the-art optical lenses and integrated eyewear. Hue.Ai uses patented coloring and dye-making knowhow to engineer sun, ophthalmic and contact lenses for the advancement of human color vision. Our lenses are loved around the world by wearers and are used by popular and prestigious eyewear brands. Hue.Ai's ColorBoost technology is also being incorporated into ballistic-protection eyewear for military and government applications.

Keenan Valentine, PhD, is the Chief Technology Officer of Hue.Ai. He is the inventor of Hue.Ai's ColorBoost technology, which is protected by 20+ patents and applications worldwide. He has a Ph.D. degree in engineering from Cornell University in the USA. WEBSITE: www.huelens.com.

Paul M. Karpecki, OD, FAAO, is the Director of Cornea and External Disease at Kentucky Eye Institute in Lexington KY. He is an Associate Professor at the Kentucky College of Optometry and is the Medical Director for KEPLR Vision. He serves as Chief Clinical Editor for the Review of Optometry Journal and is on the board of the charity, Optometry Giving Sight.

Appendix A: CRF Formulation

Using the previously discussed relations:

$$Color\ Resolution\ Factor_{Contrast\ Lens} = \frac{Color\ Resolution_{Contrast\ Lens}}{Color\ Resolution_{Clear\ Lens}} * 100\%$$

$$Color\ Resolution_{Lens} = f_1(Color\ Depth_{Lens}, Spatial\ Cutoff\ Frequency_{Lens})$$

$$Color\ Depth_{Lens} = \frac{Color\ Volume_{a^*b^*Plane\ Projected\ Area,\ \ Lens}}{Just\ Noticeable\ Difference_{Area}}$$

We derive the following important relation:

$$CRF_{Contrast\ Lens} = \frac{Color\ Depth_{Contrast\ Lens}}{Color\ Depth_{Clear\ Lens}} * f_2\left(\frac{SCF_{Contrast\ Lens}}{SCF_{Clear\ Lens}}\right) * 100\%$$

If we were to use a simplistic, physical measurement approach, then

$$Color\ Resolution_{Lens} = Color\ Depth_{Lens} * Spatial\ Cutoff\ Frequency_{Lens}$$

which would have led to $f_2\left(\frac{SCF_{Contrast\ Lens}}{SCF_{Clear\ Lens}}\right) = \frac{SCF_{Contrast\ Lens}}{SCF_{Clear\ Lens}} = Relative\ SCF_{Contrast\ Lens}$.

However, from Hue.Ai's field testing of human visual perception, we obtained the following perceptual data on the relative SCF vs. CRF, where $SCF_{Clear\ Lens}$ = 30 lp/mm for a high-quality polymer lens.

Relative SCF	0/30	20/30	30/30	40/30
CRF	~0%	95%	100%	106%

Table 1. Visual perception of relative Spatial Cutoff Frequency vs. Color Resolution Factor.

The data shows the optical resolution of a lens has a noticeable, but minor, impact on the CRF. Assuming the relationship between relative SCF vs. CRF is monotonically increasing and marginally decreasing, we derive

$$f_2\left(\frac{SCF_{Contrast\ Lens}}{SCF_{Clear\ Lens}}\right) = \left(\frac{SCF_{Contrast\ Lens}}{SCF_{Clear\ Lens}}\right)^{\frac{1}{6}} = Relative\ SCF_{Contrast\ Lens}{}^{\frac{1}{6}}$$

While the 1/6 exponent may surprise some readers, we point out such exponent relationships commonly exist between physical measurement and visual perception. For example, in CIE L*a*b* color space the lightness perception of a lens is $LT_{Relative}{}^{1/3}$—with the 1/3 exponent—where $LT_{Relative}$ is the physically-measured luminous transmittance of a lens, relative to an idealized 100% clear lens.

Consequently, we have

$$CRF_{Contrast\ Lens} = \frac{Color\ Depth_{Contrast\ Lens}}{Color\ Depth_{Clear\ Lens}} * Relative\ SCF_{Contrast\ Lens}{}^{\frac{1}{6}} * 100\%$$

$$CRF_{Contrast\ Lens} = \frac{Color\ Volume_{a^*b^*Projected\ Area,Contrast\ Lens}/JND}{Color\ Volume_{a^*b^*Projected\ Area,Clear\ Lens}/JND} * Relative\ SCF_{Contrast\ Lens}^{\frac{1}{6}} * 100\%$$

Substituting in the Color Volume Factor, $CVF_{Contrast\ Lens} = \frac{Color\ Volume_{a^*b^*Projected\ Area,Contrast\ Lens}}{Color\ Volume_{a^*b^*Projected\ Area,Clear\ Lens}} * 100\%$,

we write an elegant formula to understand and quantify the Color Resolution Factor:

$$CRF = CVF * Relative\ SCF^{\frac{1}{6}}$$

The transmission spectrum of a lens impacts CVF and therefore CRF via the above equation. Consequently, CRF measures the ability of a lens to improve color contrast.

Appendix B: CVF Formulation and the Transmission Spectrum of a Lens

The computation of CVF involves the transmission spectrum of a lens, color science, the defined set of 20 Munsell colors encircling the SCV, and a light source. We use the standard 1976 CIE L*a*b* color space to evaluate the color vision of an average person as defined by the 2-degree Standard Observer, without color vision deficiency. We use the standard daylight illuminant D65 (6500K), where its reference tristimulus values of <X_n, Y_n, Z_n> are <85.2476, 89.6946, 97.6428>, respectively, and *max*(D65) = 1 (normalized). Figure B1 shows the a*b* plane, where the horizontal a* axis substantially models the red-green opponent colors, and the vertical b* axis substantially models the yellow-blue opponent colors.

The SCV represents balanced and comprehensive warm/cool colors in an average visual environment. The 20 Munsell colors have sufficiently uniform chroma and lightness and include all major hues. These spectra sample red, orange, yellow, chartreuse, green, cyan, blue, and purple hues. Specifically, the 20 Munsell colors are: 10B 5/4, 5B 5/4, 10BG 5/4, 5BG 5/4, 10G 5/4, 5G 5/4, 10GY 5/4, 5GY 5/4, 10Y 5/4, 5Y 5/4, 10YR 5/4, 2.5YR 5/4, 10R 5/4, 7.5R 5/4, 2.5R 5/4, 10RP 5/4, 5RP 5/4, 10P 5/4, 5P 5/4 and 10PB 5/4. Their colors are shown in Figure 5 and their reflectance spectra are available publicly or from Hue.Ai upon request. Munsell colors with high chroma are not chosen, because any additional color contrast for them comparatively provides less marginal benefit if included in the SCV.

In the a*b* plane, the SCV, as seen through a clear lens, forms an approximate circle around the neutral color, shown in Figure 4 (black line). Changes in the SCV predicts the color volume effects of a lens (if any) when seen by an average person. To compute changes in the SCV, (1) scan the transmission spectrum of the lens from 380 nm to 780 nm in 1-nm resolution using a photospectrometer. (2) Then mathematically insert the data of the lens spectrum into the CIE XYZ tristimulus value calculations for each of the 20 Munsell colors encircling the SCV. (3) Use the chromatically adapted reference tristimulus values of <X_{WP}, Y_{WP}, Z_{WP}>, which are the computed XYZ values of the lens' white point (WP), in the L*a*b* computations. (4) Form the new perimeter of the SCV using the resulting a*b* values of each of the 20 Munsell colors. (5) Plot the perimeter colors of the original SCV and the new SCV in a*b* plane. (L* is sufficiently uniform and therefore obviated.)

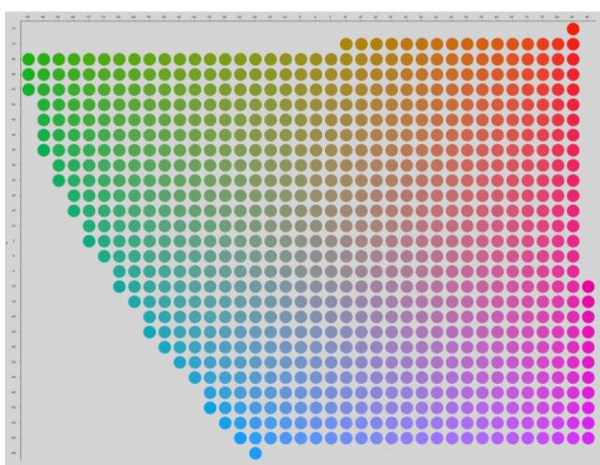

Figure B1. Illustrative a*b* plane in CIE L*a*b* color space.

Figure B2 plots the chromatically-adapted SCV of a common rose-colored lens, with its tint having L*=76, a*=31, b*=26, chroma=41.

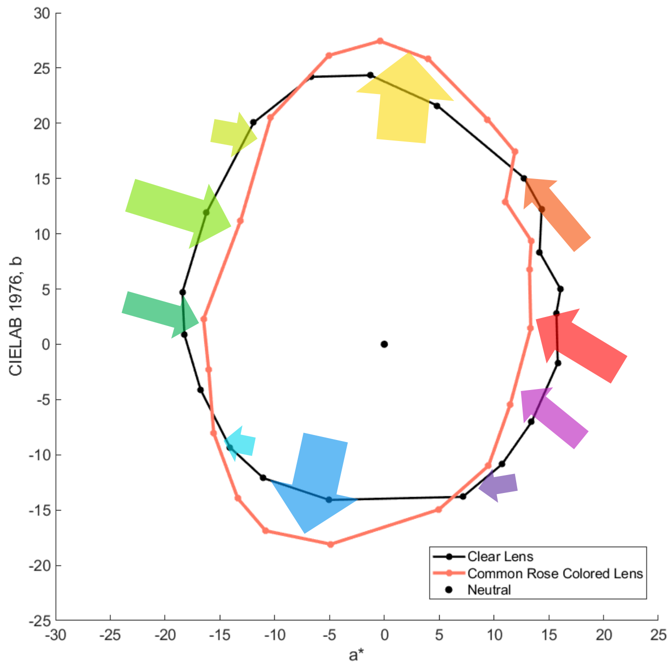

Figure B2. The SCV seen through a reference clear lens (black line) and seen through a common rose-colored lens (rose line), projected onto a*b* plane.

The rose-colored lens distorts the chromatically-adapted SCV from that of a clear lens by expanding the chromas of yellow, blue and cyan colors, while contracting the chromas of green, chartreuse, orange, red and purple colors. Overall, there is not a noticeable net change in the projected area of the color volume, and this is reflected by the lens having a CVF of 99%. The lens' measured SCF is 24 lp/mm, and therefore its CRF is 96%. Due to its prominent rosy tint, its CAF is only 56%. Overall, the CRF and CAF show this common lens has a nearly net zero color contrast and has a noticeably inaccurate transmission of colors from a typical visual environment.

Finally, the color volume and therefore CVF are further modified by accounting for the Helmholtz-Kohlrausch effect and the Hunt effect ("HK-H"). While the HK-H directly act on a color volume, it is computationally more straightforward to calculate a CVF having the HK-H using the following approximation.

$$CVF_{HK-H} \cong CVF_{no\ HK-H} * \left(\frac{0.076}{1 + 7.686 * e^{-88*\left(\frac{CVF_{no\ HK-H}}{100} - 1.058\right)}} + 1 \right)$$

where $CVF_{no\ HK-H}$ is calculated by Equation 5.

Appendix C: Existing Color Metrics, Their Shortcomings and Polarization

We briefly describe certain existing color metrics and their shortcomings if used to evaluate color contrast of a lens. ANSI Z80.3 and ISO 12312 both contain metrics, e.g., color limits, traffic signal transmittances and Q factors (Q_{signal}), designed to evaluate the suitability of a lens to recognize colored traffic signals while driving. Two drawbacks, among several, of using the Q factors to evaluate color contrast of a lens, are: (1) their dependence on only four highly saturated colors, i.e., saturated red, yellow, green (ANSI, ISO) and blue (ISO), which are not representative of common colors, and (2) some of their quantitative values do not correlate well with actual human color perception. For example, Q factors and their computational process do not involve the color components of hue, chroma and lightness. These metrics were developed for specific, safety-related purposes and therefore are limited if used to evaluate a wider array of colors.

The lighting industry commonly uses the color rendering index to evaluate the ability of a light source to produce a color volume, relative to reference illuminants. For example, an LED lamp has an index of 83 to 99, fluorescent lights have an index of 50 to 90, and an incandescent bulb has an index of 100. However, one primary drawback of this index is that its values do not correlate well with actual human color perception. Furthermore, a particular light source may not render certain colors well even though it has a high index value, e.g., an incandescent bulb does not produce blue colors well, and may not be neutral in hue.

We also briefly note that a polarized sun lens can improve color perception by reducing horizontal glare. However, the reduction of dysphotopsia is not a generally applicable metric for actual color contrast seen through a lens. Similarly, anti-reflection coatings help to reduce glare, but these coatings cannot claim to generally improve color contrast. In this white paper, we evaluate the color contrast of a lens directly from how the lens alters the colors transmitted through it via its transmission spectrum. We also note that Abbe Value and the associated chromatic aberrations of a lens are not related to color contrast as they are related to refraction.