Improving display-caused eye strain with high-accuracy colour sensors

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With modern optical filter techniques, we can now use colour filters to match the accuracy of the human eye at a cost suitable for high-volume applications

The human eye's discrimination of colours has underpinned the work of painters throughout history. Artists instinctively understand that visible light is a complex spectral phenomenon, and the proportion of red, indigo, violet, green and other colour components of white light vary in sunlight. Moreover, the colour of sunlight changes from place to place and from time to time.

Similarly, colour varies widely between different types of artificial light sources, where they can be even more pronounced and have a profound effect on electronic products. Electronic device manufacturers now understand the impact of ambient light colour on the perceived colours from a display and how to dynamically change them with illumination.

This article discusses the effectiveness of white-balancing technology and its dramatic impact on both authenticity and accuracy of colours displayed on screen.

The effect of changes in the illuminant

The spectral content of the illuminant (ambient light) affects the eyes' perception of a viewed object's colour. Viewed in daylight, at noon, objects reveal an emphasis on blue hues, because daylight consists of a distinct combination of sunlight and skylight. The same objects viewed under artificial lighting, say from an incandescent bulb (which may have a Correlated Colour Temperature [CCT] of 2700K), will appear more golden yellow. See Figure 1 for a comparison of the spectral content of various illuminants.

This effect is readily perceived by the eye when viewing an image printed on paper under different lighting conditions: the colours change as the illuminant changes. However, displays do not work this way. Until the integration of ambient light sensors in smartphones and laptop computers became common practice, a display's controller remained impervious to the characteristics of ambient light in which the display is being viewed. For this reason, displays had a fixed preset white-point colour temperature of 6500K for liquid crystal displays (LCDs) and, more recently, organic light-emitting diode (OLED) screens. 6500K was represented by the industry standards body CIE as the D65 reference illuminant shown in Figure 1, and its CCT value is similar to bright noon-time daylight, with its spectral power distribution with a strong blue component. This means that images on screen will appear very similar to those on a printed page in the same ambient condition of noon-time sunlight. Both display and printed images will give particular emphasis to blue hues. But when viewed under warmer lighting environments, such as a warm-white 3000K LED for instance, printed images appear more yellow-orange, since the illuminant has more red/yellow and less blue.

Without means of adjusting the display's white-point, electronics manufacturers have simply offered a single, fixed D65 white-point preset for their displays, resulting in images appearing with the same strong blue emphasis as before.

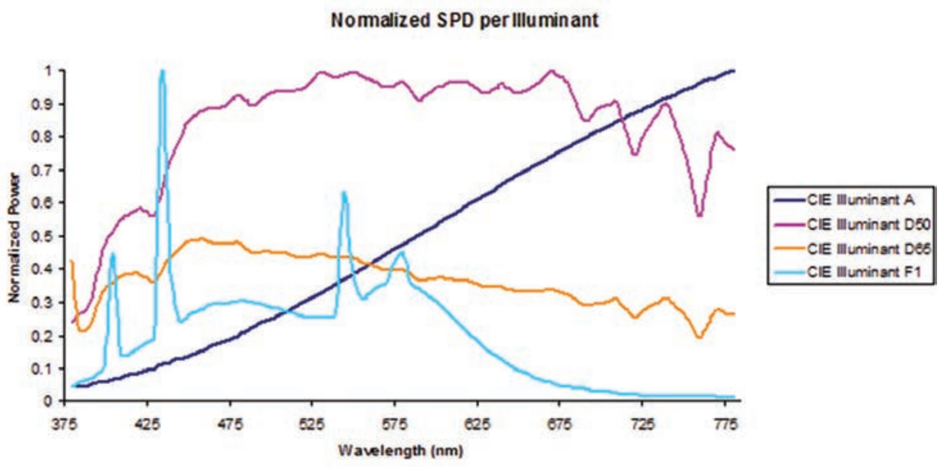

Figure 1: Spectral power distribution (SPD) of various standard CIE illuminants – fluorescent light (F1) has sharp peaks at green and orange wavelengths. This is in contrast with the broad spectrum of daylight (D50, D65) and incandescent light (A)

[Image credit: SchwartzD under Creative Commons license]

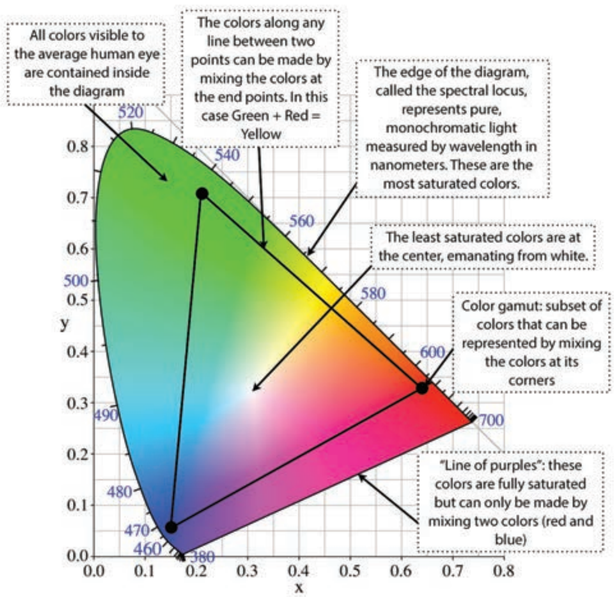

Figure 2: The standard CIE chromaticity diagram explained

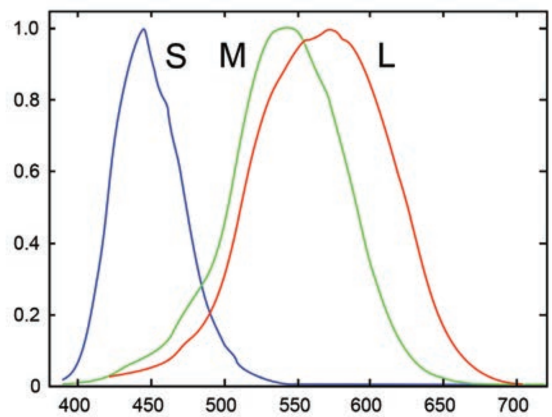

Figure 3: Normalised spectral sensitivity of human cone cells of short, middle and long wavelength types

Printed vs displayed content

We can read content from paper for many hours with minimal eye-strain. But, viewing the same content on a display with a fixed D65 white-point, emitting a significant amount of blue light, has detrimental effects, causing eye strain and disrupting sleep.

Science has shown the photobiological effects in the human eye, and hence the brain, of how blue light stimulates the waking-time physiology. Blue light suppresses the production of melatonin, the body's natural relaxing agent that helps us get a good night's sleep. The absence of melatonin makes people feel awake, potentially affecting the body's circadian rhythms.

Smartphone OEMs looking to differentiate in a slowing market can now offer a new feature called "paper-like" viewing on their displays. This is created by shifting the display's D65 cool-blue white point to a warmer colour temperature, made possible by a new generation of high-accuracy XYZ colour sensors.

With modern optical filter techniques we can now use colour filters to match the accuracy of the human eye cheaply enough for high-volume applications. These optical filters are deposited directly on to the die of optical sensor products. Traditional RGB colour sensors offer ±10% CCT, whereas CIE XYZ colour-filters' accuracy is ±1-5%.

CCT accuracy needs to stem from the colour space standard developed in 1931 known as the CIE xy chromaticity diagram; see Figure 2. Colour can be divided into brightness (or luminance, measured in lux) and chromaticity (measured in xy chromaticity parameters). The chromaticity diagram in Figure 2 is a tool which shows how the human eye will experience light with a given spectrum; it does not specify colours of objects, since the chromaticity observed while looking at an

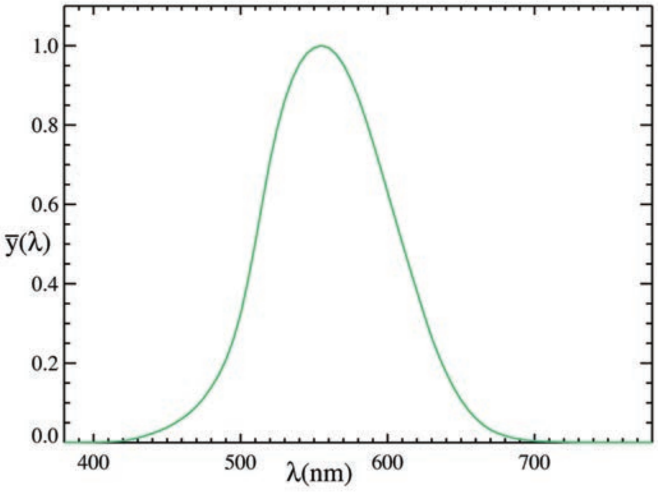

Figure 4: The green channel photopic response is closest to what humans see – from the CIE photopic luminosity function

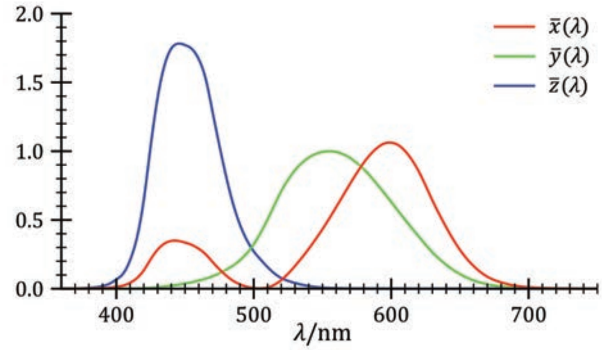

Figure 5: The CIE1931 2° Standard Observer colour matching functions or XYZ tristimulus human eye response

object depends on what colour ambient-lighting surrounds the user.

Artificial light sources tend to have warmer colour temperatures, with residential lighting the warmest (2700-3100K). Office lighting is typically 3100-4500K, whereas daylight colour temperatures range from 6000K at noon to as high as 15000K just before sunrise or just after sunset on a cloudless day.

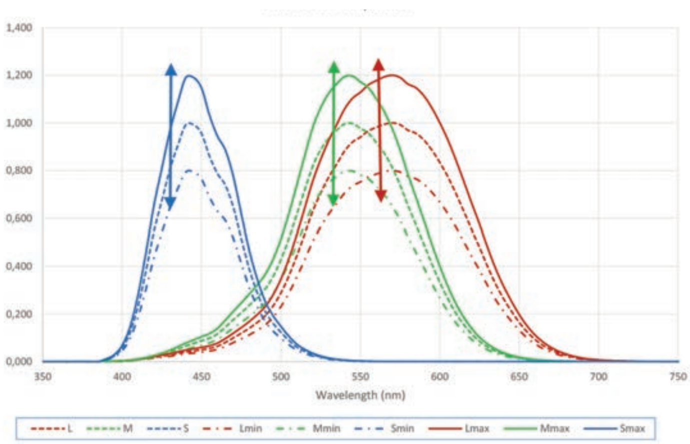

Figure 6: Chromatic adaptation

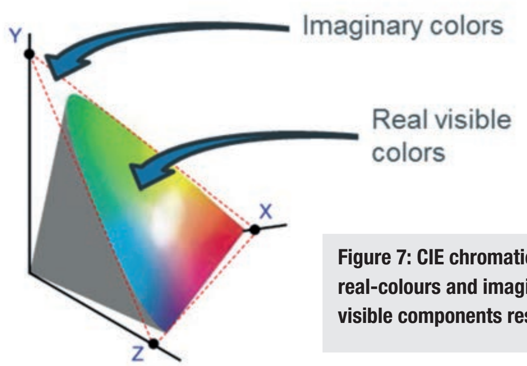

Figure 7: CIE chromaticity diagram real-colours and imaginary non-visible components response

Colour vision

Viewing a display with a white point that differs from its surroundings affects our perception of individual colours. A colour display with a neutral or cool white-point viewed in an environment with warm lighting will appear bluer than it would in a cool ambient-lighting environment. Adjusting the white point of the display to match the ambient lighting will minimise – if not eliminate – this effect.

The CIE chromaticity diagram captures the human perception of visible light wavelengths between 380nm and 780nm in the electromagnetic energy spectrum. Figure 3 shows the normalised spectral sensitivity of the human-eye's cone cells to short, medium and long wavelengths. This is driven by the neural responses of the short, middle and long cone cells of the retina, with peak sensitivity to wavelengths in the red, green or blue portions of the visible light spectrum.

The wavelength sensitivities of the cones span a rather wide range and overlap each other; each curve is normalised in the graphic for simplicity. The relative response of the three types of cone cells in the retina is sufficient to explain colour vision, and colour can be characterised by numerous sets of colour-matching functions, all of which are linear transformations of each other.

Figure 4 shows how the middle wavelength response was then defined as a photopic view and is used to define Illuminance (in lux) because the green wavelengths are closest to what we see (we are more sensitive to green and less to red and blue).

The lux is a measure of visible light illuminating a point on a surface from all directions above it, and is the unit of measure for brightness.

The XYZ tristimulus human eye response (Figure 5) was defined and is known as the CIE1931 2° Standard Observer; it provides a connection between visible spectrum wavelengths and the physiological perceived colours for colour vision.

The visual system in humans is very complex, tightly coupled to our brain. The human brain is capable of identifying an object's colour even when lighting changes. The way we see colours is not fixed but a relative perception. When the light-source type changes, humans change their perception of viewed colours because there is a dynamic relationship between an object's surface, type of light source and our eyes.

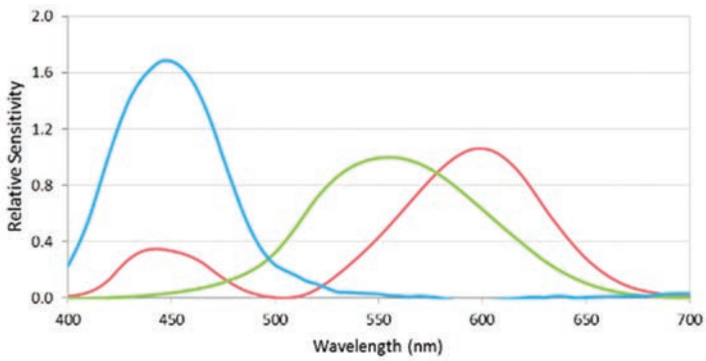

Figure 8: The XYZ spectral power distribution of the TCS3430

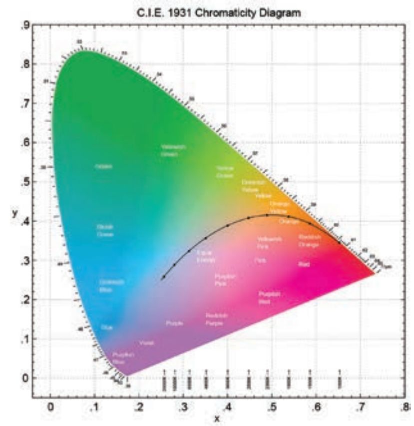

Figure 9: The CIE1931 colour space chromaticity diagram – illustrating the Planckian locus

Our visual system adjusts the relative response of the long, medium and short cone cells in response to the spectral content. Our eyes have a chromatic adaptation mechanism to understand different ambient light conditions. This is how we react to make white and grey objects look white and grey under different ambient light conditions. The optical gain adjustments for this chromatic adaptation principle are shown in Figure 6.

Figure 7 shows the real-visible colours of the chromaticity diagram and the complex imaginary components – shown in the XYZ triangle edges outside the chromaticity diagram.

RGB colour sensors are capable of measuring the real colours shown on the chromaticity diagram, where XYZ colour sensors are more accurate in measuring both real as well as complex imaginary colours. The spectral power distribution (SPD) response for a particular colour sensor is shown in Figure 8.

XYZ spectral response is based on the human eye, thereby providing more accurate information on how people perceive a colour. While there are methods to convert RGB values to XYZ, the RGB colour primaries are not an exact colour-matching function, so the resulting values from the conversion do not match how the human eye perceives colour.

By closely matching the colour response of the human eye, the data from an XYZ sensor can detect differences in colour similar to the way a human would. Using a high-accuracy XYZ colour sensor that outputs a measure of the CIE XYZ tristimulus values of incident light provides the best results when measuring ambient lighting conditions.

In Figure 9, the solid curve in the middle is called the Planckian locus. Each dot on the locus corresponds to a black-body colour temperature, which corresponds to CCT values. Adjusting the white point of the display to the ambient colour temperature assumes that the display actually knows the colour temperature of the ambient light. Since both fluorescent and LED light sources do not always fall squarely on this Planckian locus, it is better to drive the white point to the actual chromaticity coordinate values of the ambient lighting, rather than defaulting to the corresponding colour temperature on the Planckian locus.

A modern display

Figure 10 shows how this adaptive display technology works. In light boxes, two smart phones are shown in two identical pictures. Paper-like technology is demonstrated by changing the light-source. Doing so also changes our perception of the reflected colours.

Figure 10: Paper-like demo showing how pronounced blue light is in warmer lighting environments

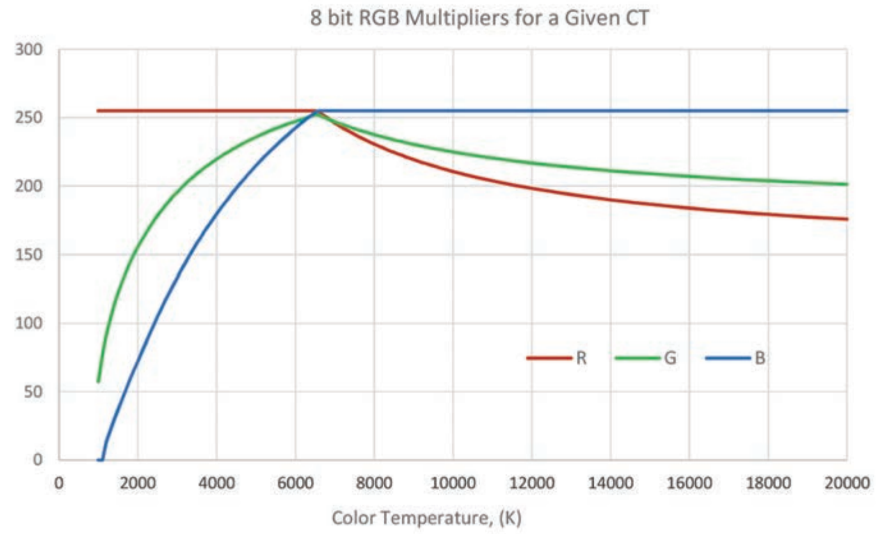

Figure 11: Recommended RGB multipliers for a given colour temperature

In the figure, the display on the right lacks an XYZ colour sensor and continuously emits D65 light. The left display has a TCS3430 colour sensor accurately measuring any changes in ambient lighting conditions; a display algorithm (Figure 11) is used to enable print-like readability.

The display has an 8-bit RGB multiplier value, so the values on the y-axis range from 0 to 256 recommendations ($2^8 = 256$), and the values on the x-axis are the measure of colour temperature values from the XYZ colour sensor. From Figure 10, for a 6500K measured colour temperature, the recommended RGB primary display driver values should be set to 256 red, 256 green and 256 blue – driving the display to a D65 white point. When a lower colour temperature is measured from a 2700K incandescent light, for instance, 256 red, 195 green and 130 blue should be displayed.

When the 6500K light bulb is illuminated, the left display measures the ambient light, applies the algorithm-recommended RGB values of 256 red, 256 green, 256 blue to drive the display to the exact same white point of the right display, making both displays look the same. The printed backboard colour content flows smoothly into content for both displays.

When the 6500K bulb is turned off and a warmer 3000K fluorescent is switched on, the ambient lighting gets warmer, and the left display automatically adjusts to a warmer white-point to match the new 3000K ambient light. The printed images appear more yellow-orange due to the blue light component being reduced.

The perceived colours we see in the printed picture are slightly changed. The display without the colour sensor continuously displays the same blue-rich D65 white-point in the warmer 3000K environment. In this case, it's clear how much bluer the right display looks, whereas the display on the left automatically adjusts its white point in reponse to the 3000K lighting environment to produce print-like readability.

Turning off the 3000K bulb and turning on an even warmer 2700K incandescent results in the ambient light growing even warmer with more yellow-orange due to less blue light content. Also, the left display and our perceived colours of the printed picture content are further changed. The left display automatically adjusts its white point to match the 2700K ambient-lighting environment in Figure 11, where the right D65 white-point display emits the same rich blue-light content.

By closely matching the colour response of the human eye, the data from an XYZ sensor can detect differences in colour similar to the way a human would

Optical filter advancements

Smartphone, computer and TV OEMs traditionally offered fixed white-points for their displays, with either a manual or time-of-day single preset white-point, with limited effectiveness since it couldn't cover varying lighting conditions. Fortunately, through advancements in optical filter techniques that yield human-eye-level accuracy at a price appropriate to the high-volume consumer electronics market, a suitable means of automatically measuring ambient lighting conditions and enabling paper-like viewing of a display is now possible.

Changing ambient lighting conditions profoundly affects our perception of viewed colours in both reflected-light environments and when viewing content on an electronic display.

Displays with fixed D65 white-points have now conclusively been shown to have physiological effects on our bodies. Automatically adjusting a display's white-point to an optimised setting under changing ambient lighting condition has noted physiological benefits – minimising the eye strain that digital technologies impose on us, whilst also allowing us to sleep better at night. EW