52.2: Display with Arbitrary Primary Spectra

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Abstract

Individual differences in colour sensation of a single display (observer metamerism) can be reduced by synthesizing and adapting the primary spectra to the physiological spectral response of the observer. The technique can also be used to synthesize the eigenspectra in multispectral imaging, and thereby provide an alternative to multi-primary displays.

1. Introduction

The colour appearance in real life is generally determined by an illumination source with a continuous light spectrum, and an object with a continuous reflectance spectrum. The light hitting the observer's retinas has a spectrum which is a product of the illumination and reflectance spectra and is therefore also continuous. In electronic displays, metameric matching is used to reproduce the same colour sensation as in real life. That is, a combination of three or more primary light sources whose combined spectra give the same colour sensation as the original product of the source and reflectance spectra. The human visual system (HVS) combines the primary stimuli, *e.g.* RGB, either spatially (subpixels) or temporally (field-sequential colour, FSC) to obtain the desired colour sensation. Two stimuli that give the same colour sensation for any observer under any circumstances need to have the same spectra; they are said to be *isomers*. Two colours that appear identical but originate from different spectra are called *metamers*. When the appearance of an object or displayed image is different for different observers in the same viewing conditions, it is referred to as *observer metamerism*.

Approximating a continuous spectrum with only three primary sources inevitably results in observer metamerism, particularly if the primary sources are saturated [1, 2]. This is because even a small shift in the observer's sensitivity spectrum by, for example, aging or changing field-of-view (FOV), has a large impact on the product of the colour matching functions and the narrow primary spectra. On the other hand, the HVS is correcting the stimuli from experience and different people therefore tend to see the so-called *memory colours* in the same way, even when their physiological spectral sensitivities are different. But if the object colour is unknown or there could be several candidates for a particular colour, memory colour in our visual system does not support the observation. In this case, a spectral match closer to real life would give an appearance that is more equal between observers, *i.e.* it reduces observer metamerism.

2. Observer metamerism in displays

Displays based on organic light-emitting diodes (OLED), RGB LEDs, or LASERs, all offer a wide gamut that enable a colour reproduction hitherto impossible. From a device engineering point of view, narrow-spectrum RGB LEDs also give higher luminous efficiency [3].

On the other hand, there is a trade-off between wide gamut and observer metamerism which, so far, has been eased [4, 5] by multi-primary colour (MPC), *i.e.* displays with more than three primaries. MPC also provides a solution to the inevitable trade-off between colour gamut and luminance in displays with broad-band light sources and absorbing colour filters.

MPC has been implemented in several configurations, for example, six-primary displays realised by two projectors with two different sets of colour filters [6] or direct-view LCDs with six different colour filters [7]. However, a finite number of primaries still result in metameric mismatches, and increasing the number of primaries further would reduce the temporal and/or spatial resolution of the display. Reducing observer metamerism is also possible by employing broader primary spectra [1, 8] but this inevitably means sacrificing of the gamut.

FSC displays with adaptive gamut (programmable chromaticities) have been proposed for projectors [9] and direct-view displays [10] using temporal and spatial superposition of the primaries. Such displays can boost luminance by up to 100% per primary for unsaturated content, decrease colour break-up, increase moving image quality, and improve ambient contrast [10]. Compared to MPCs, they solve the luminance-saturation trade-off without any increased display complexity or reduction in temporal and/or spatial resolution. However, they are based on narrow-spectrum primary sources and are thus prone to observer metamerism, especially in the case of low-chroma images for which the HVS is very sensitive to variations in memory colours such as white and skin colours. This problem also manifests itself in on-screen metamerism [4] of RGBW displays where W is generated directly from the backlight; White by RGB and white by W look different.

One objective of this paper is to propose a display with adaptive gamut *and* reduced observer metamerism. Desaturation is achieved through primary spectra synthesis (broadening) rather than superposition of fixed narrow spectra.

While not touched upon here, it is also possible to adapt such a display to observers with colour vision impairments or age-related physiological changes, without transformation of the image data.

3. Multi-spectral imaging

To accurately capture and reproduce the appearance of any object for any observer under any circumstances, it is necessary to record the reflectance spectrum for each pixel and multiply with the spectrum of the desired light source (multi-spectral imaging). While such an approach involves redundancy and produces an exceedingly large amount of information, a linear combination of *eigenspectra* can fully describe the original spectrum. For example, it has been found [11] that only three and five eigenspectra are sufficient to fully reproduce the original reflectance spectra of human tissue and oil paintings, respectively. For any image, a maximum of seven primaries is necessary to reproduce the original spectrum [12]. Therefore, a display with eigenspectrum primaries requires only between three and seven channels and the uncompressed video bandwidth to the display would therefore be approximately the same as in conventional three-primary or multi-primary displays. However, established compression techniques such as JPEG need to be extended to include spectrally encoded images.

Cameras with tuneable, narrow band-pass colour filters are readily available, so it is possible to record a good approximation of the continuous spectrum of each pixel and encode the image into a linear combination of the eigenspectra.

The large freedom of spectrally designing printing inks and display colour filters allows reproduction with spectra very close to the eigenspectra. However, the eigenspectra are different for different kinds of objects so one set of inks or colour filters cannot be used to reproduce the appearance of an arbitrary object. The solution to this is to increase the number of inks or primaries so that any continuous spectra can be reproduced with a good approximation. However, this leads to system complexity and reduced temporal and/or spatial resolution.

By contrast, reconfigurable primary spectra enable a display for multi-spectral imaging with a manageable number of data channels.

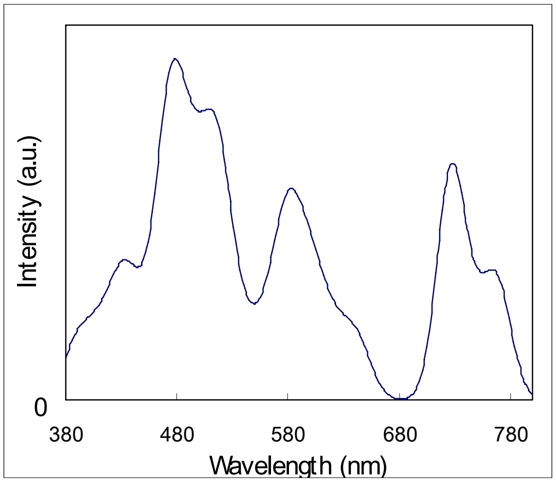

Figure 1: Example of a spectrum synthesized by 20 Gaussian light sources all with 30 nm line widths and same peak heights, but with peak wavelengths spaced at 21 nm from 390.5 to 789.5 nm. The relative fluence weights are 1,1,2,1,5,3,4,1,1,3,2,1,1,0,0,0,4,1,2,0, respectively

4. Spectrum synthesis

Spectrum-sequential displays have been proposed [13] but only with fixed sets of backlight and colour filter spectra. RGB organic light emitting diodes (OLEDs) with the spectrum tuneable by driving frequency and pulse width modulation (PWM) have been proposed [14] but it relies on a fixed ratio between the decay times of the red, green, and blue emitters, which therefore limits the chromaticity range.

Arbitrary spectrum synthesis for display primaries is realised by utilising the finite response time of the eye. FSC displays also utilise this fact but the integration time is one *frame*, and the display shows colour-separated images during each *field* (temporally additive colour). The display proposed here is an extension of FSC displays in which the light integration takes place *separately* for each field or subfield (digital greyscale), with constant image data shown on the display during the integration period (primary source superposition). Field-wise [9, 10] and subfield-wise [15] superposition has been proposed but the time-integrated spectra were limited to a linear combination of the spectra of three light sources (LEDs). Although the display chromaticites are adjustable, continuous, smooth primary spectra could not be synthesized.

The proposed FSC display uses a relatively large number of independently controllable light emitters, each with a different spectrum. Each colour plane (bit plane in the case of digital driving) can therefore have different backlight spectra. Fig. 1 shows an example of a spectrum from 20 light sources with Gaussian emission spectra. By increasing the number light sources with different wavelengths, precisely varying the relative fluence weights, and averaging over time, synthesizing spectrum with good accuracy is possible.

5. Implementation

Recent advances in wavelength binning [16] of LEDs and fabrication of quantum dot (QD) emitters [17] have enabled Gaussian spectral power distributions with a peak wavelength accuracy of ±0.5-1 nm and full width at half maximum (FWHM) of 15-30 nm. The narrower the line width, the higher wavelength resolution at which the primary spectrum can be synthesised. It is also possible to customise *fixed* spectra by mixing QDs of different sizes and/or kinds – these spectra will themselves be a combination of Gaussian spectra minus the self-absorption part. The QDs can be selectively printed on top of microscopic arrays of independently addressable LEDs [18] which optically excite the QDs so that they emit fluorescent light of various spectra.

While accurate spectrum synthesis in large displays requires a prohibitively large number of devices, direct-view mobile displays and near-to-the-eye displays do not need more than one emitter per peak wavelength. Also, progress in miniaturisation of LED dicing and packaging allows close packing of many devices into a small area which ensures good colour mixing. LEDs with and without phosphors are now available across the entire visible range with line widths of typically 15-25 nm, even narrower with resonant cavity (RCLEDs). The fluences can be controlled either by emitter current, duty cycle, or a combination thereof.

Implementing spectrum synthesis for MSI is as follows. First, the eigenspectra are determined by measuring the reflectance spectra of various object categories. This has been done for a large number of categories such as oil paintings, human tissue (medical imaging), apparel, cosmetics, and skin colour [11]. The image is then recorded by a multi-spectral camera and the image is encoded in terms of eigenspectra channel weights, and the eigenspectra are embedded into the image data container. The eigenspectra and weights may also include the effect of an illuminant of choice.

The display unit receives the image, extracts the eigenspectra data and synthesize the eigenspectra. With Gaussian emitters, this resembles to an eigenvalue problem with the Gaussian normal distribution functions as (non-orthogonal) eigenfunctions. This can be solved in an iterative process which will give the result in form of relative fluence weights of the light sources for each field. If the light source spectral distributions are known at the stage of image encoding, the fluence weights can be directly embedded into the image and the iterative process is not needed.

To reproduce each pixel spectrum, the eigenvalues are written to the display for each field, during which the corresponding eigenspectrum is synthesized by the backlight system. This is done by loading fluence weights to the light source controller which switches on the light sources accordingly during the field.

6. Results and discussion

To compare the two different approaches to adaptive gamut from an observer metamerism point of view, we construct two sets of primary spectra both of which yield sRGB chromaticities. Further reduction of the native source gamut is possible but this serves as an illustrating example. The first set is created by a linear combination (superposition in FSC) of fixed-spectra, narrow-band RGB emitters. There exist three so-called *prime* wavelengths which minimise the effects of observer metamerism [1] in narrow-band RGB displays; 610, 540, and 450 nm for red, green, and blue, respectively. However, their chromaticities do not correspond to the sRGB hues so gamut reduction by a scalar desaturation factor [10] does not yield the sRGB chromaticities. Instead, we numerically find the dominant wavelengths of the sRGB chromaticities with D65 white, R=611.4 nm, G=549.4 nm, B=464.5 nm, and use those in a Gaussian, narrow-spectrum (FWHM=5 nm) emission model. The sRGB chromaticities are then obtained by superposition of these primary spectra using weights corresponding to the CIE1976 *u'v'* distance between their chromaticities and sRGB RGB chromaticities, relative to D65 and along the constant-hue lines (desaturation factor, see Ref. 10).

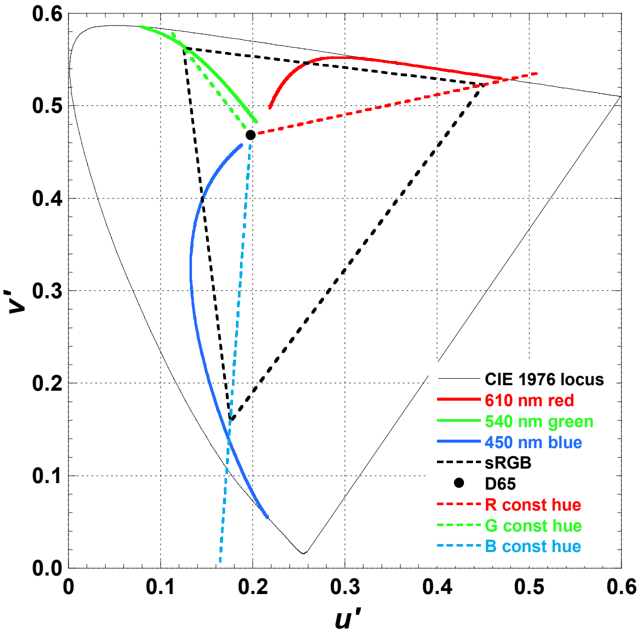

Figure 2: sRGB chromaticities and constant-hue lines (dotted) and traces of Gauss broadening of prime-wavelength emitters (solid)

In the spectrum synthesis approach, we considered simple Gauss broadening of the emission peaks corresponding to the prime wavelengths. The solid lines in Fig.2 show traces for FWHM=1…400 nm. It can be seen, however, that the trajectories never reach the sRGB chromaticities and that they do not follow the constant hue lines.

Instead, we varied both the peak wavelength and the FWHM by numerically searching (wavelength/FWHM step 0.1/1 nm) the combination that gives the minimum $\Delta E_{u'v'}$ with respect to the sRGB chromaticities. While this works for blue and green, some superposition of blue and green onto red is necessary to reach the sRGB chromaticity for red. This was expected since the overlap between the red and green colour matching functions (CMFs) is large. For sRGB blue and green, the Gaussian peak wavelength/FWHM combinations are 415/151, and 539/101 nm, respectively, and give the correct chromaticities with three significant figures. sRGB red can be obtained by superpositioning the broadened blue and green on to the narrow red with the same weights (9% desaturation) as in the first approach. However, this would produce a very sharp red peak and hence metamerism. Instead, we choose a typical red FWHM value of 50 nm and numerically determined the peak wavelength to 628 nm (sRGB red hue). The desaturation factor was determined geometrically to 8% to achieve sRGB red. It is possible to achieve the same hue with larger FWHMs but that requires longer (>650-700 nm) peak wavelengths and hence more spectral energy at wavelengths at which the eye sensitivity is very low. The spectra resulting from the two approaches are shown in Fig.3.

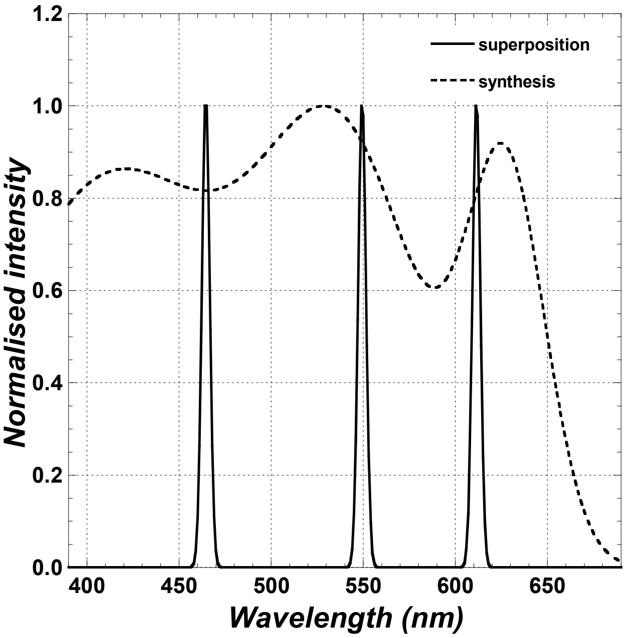

Figure 3: Two spectra that both correspond to white by sRGB chromaticities; Superposition of narrow-band primaries (solid line) and synthesized (dotted line) broad blue and green plus superposition of Gaussian red with a FWHM of 50 nm.

Next, we calculate $\Delta E_{u'v'}$ for white in the two approaches, varying the age parameter in the colour matching functions of the CIE2006 physiological model [1, 19]. This gives us a quantitative indication of the amount observer metamerism, and its dependence on age. The result is shown in Fig.4. The colour difference is larger for superpositioning although the absolute difference is rather small. This can be attributed to the fact that smaller FOVs (6º typical in handhelds) give smaller age-related colour differences [1]. Also, a red FWHM of 50 nm was chosen rather arbitrarily – broader red can reduce colour shift by age further.

Combining broadening with superpositioning also in the blue and green to shrink the gamut would reduce the number of necessary sources and increase the power efficiency since the tails in the near-UV and deep red would disappear. Balancing of the power consumption, observer metamerism, and gamut therefore requires simultaneous adjustment of the peak wavelengths, FWHM, and superposition ratios. Finding the optimum synthesis weights for such a configuration is, however, beyond the scope of this paper.

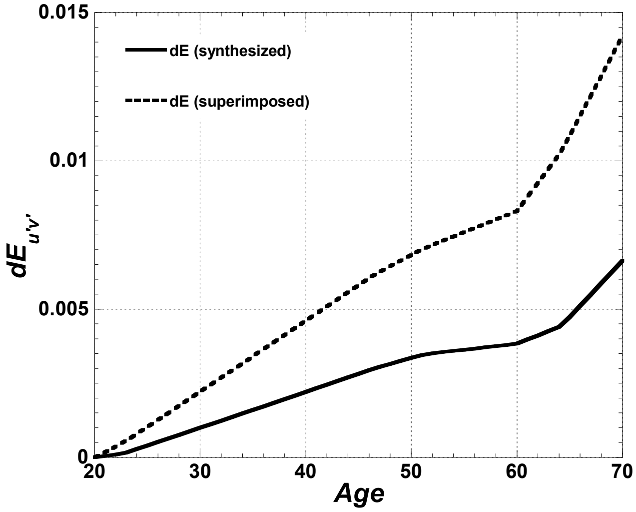

Figure 4: Relative colour difference with respect to sRGB white created by spectrum synthesis and superposition, respectively. CIE2006 physiological CMFs are used with a 6-deg FOV.

6. Conclusions

A field-sequential colour display with primary spectra synthesized by a temporally-averaged, modulated array of light sources, is proposed. Implementation of adaptive gamut via spectrum synthesis (broadening) reduces observer metamerism compared to superpositioning of narrow-band primaries. The display also enables multi-spectral imaging with applications such as colour-critical electronic commerce, virtual art museums, high-accuracy remote medical imaging, digital archive and browsing. As a conventional 3- or multiprimary display, it provides a means to adapt the appearance to chromatically impaired observers, without the need of manipulating image data

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8. References

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