

# Application of digital micromirror devices to vision science: shaping the spectrum of stimuli.

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## ABSTRACT

In vision and color research, it is often desirable to precisely control the spectral content of light stimuli. Some demanding research applications require replicating or producing natural or novel complex spectral illumination. However, complex spectral distributions, common in the real world, often prove difficult to simulate in the lab. Past researchers have combined LCD technologies with broadband sources and wavelength dispersing elements, such as gratings, to produce approximations to natural distributions. These devices have been limited in contrast, temporal resolution, and precision by the nature of the LCD itself. We show here how a spectrally-dispersed broadband source modulated with Digital Light Processor (DLP) technology provides for rapid and precise spectral shaping of visual stimuli at intensity and precision levels previously unattainable using other light modulating technologies, and present a sample application consisting of data from color vision experiments designed to probe the visual system's differential response to narrow versus broad band color stimuli.

**Keywords:** DLP, illumination, color vision, Abney effect, natural spectra

## 1. Introduction

### 1.1 Objective

Advances in optics and image related sciences are often limited by the available technology. This is certainly true for research in the vision sciences. Great advances in the understanding of visual processing have often occurred after technological innovations such as the microscope, electron microscope, MRI, CRTs, lasers, LEDs, and LCD panels. For research in color vision, improved methods of stimulus generation have been critical for many recent advances. In particular, LCD panels and digital micromirror devices have allowed for precisely defined and rapidly changing patterned stimuli to be combined into traditional Maxwellian-view or projection systems for use as visual stimuli. In addition, there are recently developed methods that extend the spatial and temporal shaping capacities of these technologies into the spectral realm<sup>1,2</sup>. We describe here applications for color vision research that utilize a micromirror-based device that provides the capacity to precisely shape the spectral (and temporal) output of a broadband light source.

### 1.2 Need for spectrum shaping

Models for understanding the neural basis for color vision capacities have enjoyed various degrees of success. For some instances the percept of color dimensions (hue, saturation, and brightness) are well predicted by standard color vision models based on the relative activity of the three cone classes. However there are many instances wherein standard color vision models fail to predict the percept. In particular, judgments of "unique hues", (colors that appear "pure" and without other hues) and of which mixtures constitutes "pure white" are not well predicted based simply upon activations of the different cone classes. Furthermore, there is evidence that judgments of unique hues and white



are relatively stable over the lifespan, despite large spectral shifts caused by age-related changes in pigments of the eye<sup>3,4</sup>. These results suggest that long-term exposure to spectral properties of the environment greatly shape the percept of hue. Results that demonstrate spectral biasing of hues after long-term exposure to a spectrally-shifted environment underscore the important role for environmental factors in color perception.

One of the most important ways in which colors in the natural environment differ from those in typical laboratory settings is in bandwidth. Most surfaces in the natural environment reflect light over a large part of the spectrum whereas in most laboratory experiments the chromaticity of the light is controlled by relatively narrow band sources such as a monochromator or medium-band sources such as the three phosphors of CRT displays<sup>5</sup>. It has been suggested that one of the ways in which the human color vision system retains constant hues or judgments of white despite the large spectral changes described above is by implicitly assuming stable natural spectral properties. These properties are essentially “learned” by the system during long-term exposure. (It is important to note, that such “learning” could be at the most basic levels of neural adaptation and would not require higher cognitive processes). Thus, when tested in laboratory settings, failures in hue judgments can arise due to violations in the assumption of natural spectral properties. Recently, Mizokami et al.<sup>2</sup> have suggested such an explanation for the failure to predict the hues of spectrally narrow band lights that have been desaturated by the addition of a broad-band white light. When white light is added to a wavelength the perceived hue changes, a classic phenomenon in color appearance known as the Abney effect. For example, a short wavelength light appears more purple as it is desaturated, while a long wavelength light appears more red. To match the hue of these wavelengths the dominant wavelength of the desaturated stimulus must be shifted to longer (for short waves) or shorter (for long wavelengths), or in other words away from the extremes of the visible spectrum. These hue shifts reflect a nonlinearity in color appearance, because constant hues do not correspond to constant relative outputs in the cone receptors and thus do not fall along straight lines in color space. However, Mizokami et al.<sup>2</sup> suggested that the loci of constant hues could reflect an attempt by the visual system to correct for its own spectral filtering characteristics, so that perceived hue is tied to a consistent property of the stimulus rather than a consistent property of the neural response. Specifically, they suggested that perceived hue might correspond to the inferred peak or modal value of the spectral distribution. To test this assumption they performed hue matches between lights with Gaussian spectra that could be varied in hue by changing the peak wavelength and varied in saturation by changing the bandwidth. Their results supported the proposition that the Abney Effect – rather than representing a failure of the visual system to consistently encode hue – actually represents a strong tendency toward hue constancy in which constant hues correspond to constant features of the physical world (e.g. the spectral peak of the stimulus) rather than constant properties of the observer (e.g. constant cone ratios).

The above results illustrate one of many potential examples where understanding human color vision requires experiments which have the capacity to control and to precisely mimic naturalistic spectra. In the experiments of Bonnardel et al.<sup>1</sup> and Mizokami et al.<sup>2</sup> spectral shaping was done by passing the broad-band light source through a spectral dispersion element followed by filtering the intensity of the different spectral regions using LCD technology. The filtered spectral components are then recombined prior to output. These devices provided for limited spectral shaping intensity ranges owing to inherent limitations in the hardware. We employed a recently developed and improved system for spectral shaping, a commercially available device named the Agile Light Source- OL 490 (Optronic Laboratories). This has allowed us to revisit the relationships between hue and saturation and physical spectra with greater stimulus control and for a wider range of stimuli. We further demonstrate the ability of this device to mimic actual distributions of light in the natural environment or to synthesize arbitrary distributions like Gaussian spectra. This offers the potential to explore a number of novel questions and applications in color research.

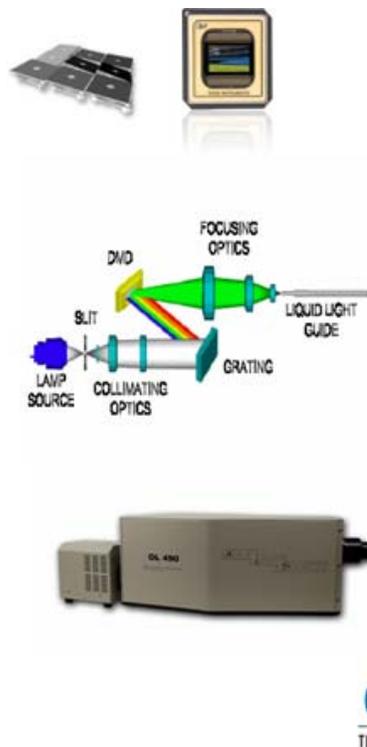
## 2. Methodology

### 2.1 Agile Light Source –OL-490

Digital micro-mirror devices (DMD) are a product of MEMs technology developed by Texas Instruments and the central component in Digital Light Projection (DLP<sup>®</sup>) displays. Coupled to a broad band source illuminating a dispersive element, such as a spectral grating, the DMD can be used to select specific band-passes or entire spectral profiles while

varying their intensity. These spectra can be modulated, combined and transmitted via liquid light guide or other output to the sample in an imaging platform.

Such sources can produce emissions at a single wavelength or broad spectrum, steady state or varying with time. The OL 490 Agile Light Source used in our work (see **Figure 1**) offers programmable and variable high intensity and high resolution spectral output, delivering an impressive level of flexibility and speed to a wide range of applications. A stable 500W Xenon lamp source generates output intensities exceeding that of conventional monochromator sources, (>250 mW across a spectral range of 380 nm – 780 nm). Using a 1,500W Xenon source, the output can be tripled. By varying the slit width, the user can trade off between resolution and output power depending upon the application. The control software enables operators to set multiple bands, sweeps, and trigger modes via direct USB computer control to produce almost any desired spectrum, combination of spectral lines, modulation or sequence with a switching rate of 12,500 spectra per second and a range of over 49,000 intensity levels output to a 3 mm liquid light guide. In our application, the light guide was connected to the input port of a 8 inch integrating sphere (Oriol). The output port of the integrating sphere was 5 cm in diameter and served as the stimulus field for hue judgments.



**Figure 1 - Agile Light Source**

## 2.2. Procedure

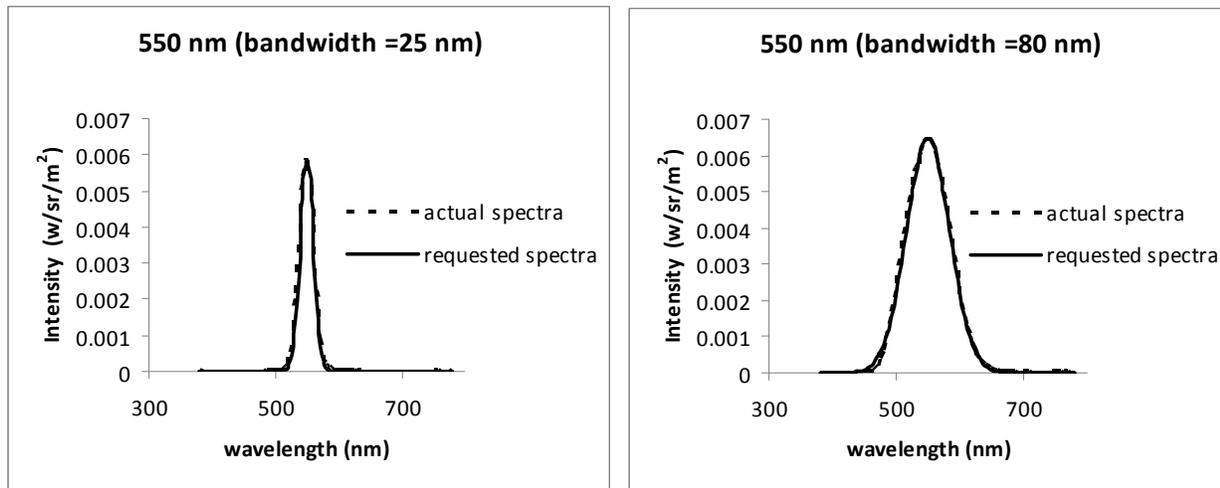
We used the OL 490 to measure the perceived hue of different spectral stimuli. Participants were seated approximately 57 cm from the integrating sphere and freely viewed the exit port in an otherwise darkened room. Subjects were asked to make hue judgments between two stimuli that were presented in temporal sequence. A reference stimulus was composed of light with a Gaussian spectral distribution, a fixed peak wavelength, and a bandwidth (full-width at half-height) of 80 nm. The test light was also spectrally distributed as a Gaussian with a bandwidth of 25 nm at half-height. The reference light appeared for 1 second followed by a dark period of 0.5 seconds and the test stimulus for 1 second. To make a hue match, the peak wavelength of the test was adjusted using a two-alternative, forced choice procedure with 2 interleaved staircases. For example, the subject was asked to judge if a test light with a 450 nm peak was “more violet” or “more blue” than the reference light by pressing different buttons on a response keypad. The choice given to the subject varied

according to the reference light. Thus, for the green part of the spectrum the subject was asked if the test light was “more yellow” or “more blue” and so on. The staircases varied the peak of the test light to estimate the point at which the two alternative responses were given with equal frequency, corresponding to the wavelength at which the narrow test and broad reference match in hue. Hue judgments were made using reference lights from 450 nm to 650 nm in 20 nm intervals. All light measurements and calibrations were made with a Spectrascan PR650 (Photo Research).

### 3. Results and Discussion

#### 3.1 Capacity for the OL 490 to generate desired spectra.

Examples of data demonstrating the ability of the OL 490 source to generate the desired spectra are shown in figure 2. The left panel of the figure plots the data for the 550 nm Gaussian profile with a 25 nm bandwidth. The data for a Gaussian distribution with a bandwidth of 80 nm are shown in the right panel. The output requested from the light source is shown (solid lines) as well as the actual output of the source (broken lines) as measured with a Photo Research PR 650. As can be seen, the output of the light source accurately rendered the requested distribution.. Similar levels of precision were obtained for Gaussian profiles from 450 nm to 650 nm.



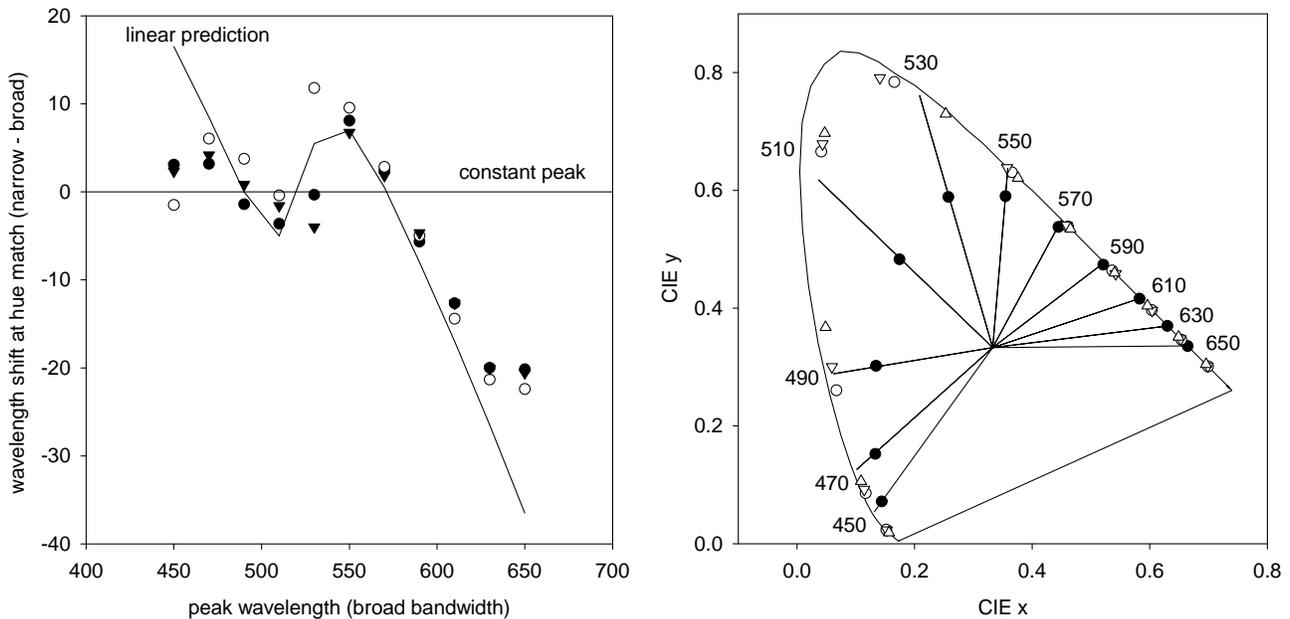
**Figure 2. Examples of Gaussian Spectra used in the hue matching task. The data for a Gaussian spectrum with a peak at 550 nm and a bandwidth of 25 nm are shown on the left. The data for a Gaussian spectrum with a peak at 550 nm and a bandwidth of 80 nm is shown on the right. Both requested distributions and actual distributions are shown.**

#### 3.3. Hue matching data

The results from hue matching are shown in Figures 3 in terms of the matching peak wavelengths (Fig 3a) or matching chromaticities in the CIE 1931 chromaticity diagram (Fig 3b). For the three observers tested, the narrow and broad stimuli matched in hue when their peak wavelengths were equal in the blue and blue-green region of the spectrum ( $\leq 510$  nm) and near yellow ( $\sim 570$  nm). Alternatively, the matching peaks differ in the yellow-green ( $\sim 550$  nm) and in the orange and red regions of the spectrum ( $\geq 590$  nm). The results thus fall in between the predictions for either complete compensation, so that hues are tied to a constant peak (flat line at 0); or the predictions for no compensation such that the hue is determined by constant ratios of the cone excitations (line shown as linear prediction). The deviations from linear cone ratios are further seen in the CIE coordinates for the matches in Figure 3b. Here the linear predictions plot as lines of constant slope emanating from the nominal white point (equal energy white). The fact that the matching chromaticities for the narrow (open symbols) and broad (closed symbols) spectra do not fall on common lines over most of the spectrum reconfirms the strongly nonlinear relationship between hue and saturation that defines the Abney Effect. The importance of the present results is in showing that this nonlinearity may in fact reflect a functional adjustment in color coding so that hues tend to match when properties of the physical spectra (e.g. their peaks) match. This may be

advantageous in color vision because it allows hue percepts to more clearly convey information about the spectral qualities of the stimulus than the spectral sensitivity limits of the observer.

The second important point is that the present device allowed us to explore the questions posed by Mizokami et al (2006) over a larger range of the visible spectrum and with much greater accuracy. As noted, the present results show that the matches do not faithfully tie hue to the spectral peak at all wavelengths, and in particular fail markedly at longer wavelengths. The observed pattern suggests that there may be two distinct regimes in the hue matches. At shorter wavelengths there is almost complete compensation for the perceived hue so that peak wavelengths match even though the cone ratios must therefore vary. (Notably, this is the region to which most of the measurements in Mizokami et al (2006) were restricted). At longer wavelengths – which have not been previously tested in this way - there is instead only partial compensation, so that equivalent hues do not reflect equal peaks in the spectra, yet the matches are still shifted away from constant cone ratios in the direction of constant peaks. It is unclear why the effects measured in terms of peak wavelength are asymmetric at shorter and longer extremes of the visible spectrum, since the nonlinearities of the Abney Effect appear similar at either end. However, a tantalizing possibility is that sensitivity at shorter wavelengths is limited by very different factors (the inert screening pigments in the lens and macular region of the retina) than sensitivity at the red end of the spectrum (which is instead limited by the sensitivities of the long (L) and medium (M) wavelength sensitive cones). A further possibility is that the failures at longer wavelengths correspond to a region of the visible spectrum which is visible only to the L and M cones and not to the short-wavelength sensitive (S) cones. In either case this could indicate that the visual system can only learn and compensate for some of the factors that constrain spectral sensitivity. It could also mean that the spectral peak assumption or the assumption of Gaussian profiles is too simplistic, and that hue percepts instead correspond to some other inference that the visual system is making about the stimulus.



**Figure 3. Hue matches between narrow and broadband spectra. a) Differences in the spectral peaks of the narrow and broad Gaussians at the match point, as a function of the peak of the 80 nm bandwidth reference light. Symbols show the matches for 3 different observers. Lines show the predicted matches if the match occurs when the peak wavelengths are the same (constant peak) or when the relative cone ratios are the same (linear prediction). b) The hue matches replotted by their coordinates in the CIE 1931 space. Filled symbols show the coordinates of the broadband reference spectra; open symbols show the matching chromaticities chosen by the 3 observers for the narrowband stimuli. Radiating lines show the matches predicted by constant linear cone ratios.**

### 3.3. Reproduction of more complex spectra

The results illustrated above demonstrate the utility of the OL 490 to generate stimuli that differ in spectral compositions in ways that allow novel tests of models of color appearance. There are many other cases where the capacity to generate complex spectra would prove valuable to probe human color vision. For example, individuals differ in their spectral sensitivity and thus color sensitivity and appearance cannot be accurately represented by a single “standard observer.” Measuring how individuals respond to different spectra is important theoretically for exploring the mechanisms of color coding and important practically for understanding applied questions such as color rendering across illuminants and media. A central issue is how the visual system responds to the complex and broadband spectra that characterize natural illuminants and surface reflectances. Such spectra are typically complex and thus difficult to simulate with traditional technologies. However, Figure 4 shows that such complex spectra can be readily generated with high fidelity in the OL 490.. Thus such devices open may new directions for color research.

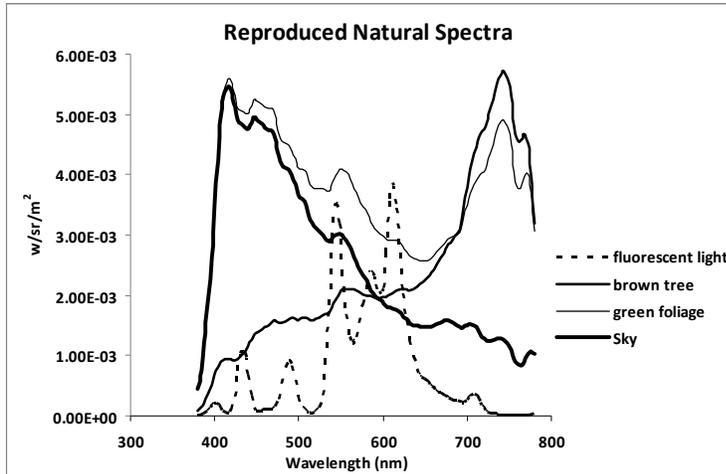


Figure 4. Output of the OL 490 when programmed to simulate reflectance from the natural environment and from fluorescent lighting. Four different spectra are shown with various degrees of complexity.

#### 4. Conclusion

The results presented here demonstrate the utility of using a DLP-based system to shape the spectrum in research on human color vision. The OL 490 produced spectral lights that closely matched those of the model (Gaussian). Precision of control over the spectral bandwidth of test stimuli reveals effects of spectral composition on the perception of hues. These percepts are not easily modeled by relative cone activations and require additional explanation. These data support the proposal that hue percepts may be more closely tied to properties of the natural environment (e.g. broad-band spectra) than to actual relative cone excitations, though they leave for future research the question of which properties and to what extent color vision is matched to the color environment. The OL 490 provides a novel and important tool for addressing questions of this kind. In addition, we show how the OL 490 can be used to generate any arbitrary complex stimulus including those of artificial light sources and reflectances in the natural environment. Such stimuli have broad application to research in human vision. Finally, the precise control over the temporal properties of the output provided by the OL 490 complements the spectral capacities of the device and further enhances its potential applications.

#### 5. Acknowledgments

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