

Unique hue and spectral bandwidth

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ABSTRACT

A central question in color vision is: to what extent are the unique hues tied to properties of the environment versus properties of observers? We are exploring this by asking how the unique hues vary with changes in the spectral bandwidth of the stimuli, for which environmental and physiological accounts make different predictions. Selective filtering by the lens and macular pigment differentially biases the spectrum of broader bandwidth lights relative to narrower bandwidths. We examined the extent to which these biases influence differences in perceived hue both across individuals and within the same individuals at different retinal eccentricities. Differences across observers were compared to two possible models of the unique hues (based on assuming a common set of cone ratios or a common stimulus in the environment) which differ in predicting either a decrease or increase in interobserver differences as the spectrum narrows. The results did not clearly support either model implying the unique hues are relatively unaffected by the filtering effects of screening pigments and that differences between observers may reflect different weightings of the cone signals or normalization to different stimuli in the environment.

1. INTRODUCTION

The color appearance of any aperture light can be described by combining different pairs of the four unique hues: red, green, blue, and yellow. The unique hues themselves appear as pure and irreducible sensations, and are thus important to models of human color appearance (Abramov and Gordon, 1994). Observers vary widely in the specific spectral stimuli that they choose for unique hues, but the bases for these individual differences remain uncertain (Scheffrin and Werner, 1990; Webster et al., 2000). One suggestion is that the unique hues isolate postreceptoral channels that draw on specific combinations of the cone signals (Kaiser and Boynton, 1996), so that individual differences arise from physiological factors such as, for example, differences in the relative numbers of cone receptors (e.g. Cicerone and Nerger, 1989). An alternative is that they correspond to learned properties of the visual environment (Pokorny and Smith, 1977), so that interobserver differences reflect the nature of our experience with color signals. We tested whether the unique hues are consistent with a fixed rule for weighting the cone signals, by asking how unique hues vary as the spectral bandwidth of the light changes from narrow (e.g. monochromatic) to broadband. Selective filtering by the lens and macular screening pigments reduces sensitivity at shorter wavelengths, and is a major factor contributing to individual differences in color matching (Webster and MacLeod, 1988). This screening differentially biases the spectrum of broader bandwidth lights relative to narrower bandwidths, and thus alters the dominant wavelength of the light reaching the receptors. To maintain a fixed cone ratio, the dominant wavelength of the stimulus must shift toward shorter wavelengths as the stimulus bandwidth increases. Thus a fixed weighting – whether innate or learned – predicts that the dominant wavelength chosen for the unique hues will vary with bandwidth. On the other hand, environmental and physiological accounts make different predictions about how the unique hues should vary across individuals (who might vary in ocular pigment density) and within the same individuals at different retinal eccentricities (which differ in macular pigment density). If the unique hues are determined by a fixed ratio of the cone signals, then individual differences should be smaller for narrowband stimuli than broadband. This is because the stimuli required to maintain this ratio should diverge as the spectrum is broadened and as individual differences in ocular density come to play a larger role. That is, narrowing the spectrum removes one potential source of physiological variation, and thus should lead to greater consensus across observers. However, if the unique hues instead reflect learned stimuli in the environment, then differences in the hue

settings should instead be larger for narrowband stimuli. In this case, this is predicted to occur because natural color signals are very broadband while narrowband stimuli are rare (Maloney, 1999). Suppose that observers learn to agree about the natural color signals they label as pure green, even though these signals are filtered in different ways by their individual eyes (Jordan and Mollon, 1995). As the spectrum is artificially narrowed, each observer might choose a stimulus that preserves the cone ratio they learned from the broadband stimulus, and these will diverge as the screening pigments now become less important in shaping the spectrum. Thus the experiential account predicts that learned consensus for broadband stimuli will break down for narrower spectra. Note that similar predictions also apply to the color judgments of a single observer for stimuli viewed at different retinal eccentricities, since the macular screening pigment is limited to the central retina. We therefore compared the predictions for physiologically and environmentally determined models of the unique hues both for different observers and for the same observer in foveal and peripheral viewing, and asked to what extent either model could account for actual measurements of the changes in unique hues between narrow and broadband stimuli.

2. MODEL METHODS

Predictions were based on calculating the unique hue loci for a set of simulated color-normal observers who differed in lens and macular pigment density and in the spectral peaks of the long, medium, and shortwave (L, M, and S) cones. The spectral sensitivities for individual observers were reconstructed from a factor analysis of the 49 observers in the Stiles and Burch 10 deg field color matches (Webster and MacLeod, 1988), following procedures described in Webster et al. (2000). For the common LMS ratio model, we calculate for each observer the stimulus required to produce the same angle relative to white (Illuminant C) within an LvsM and SvsLM chromatic plane. The chosen angle corresponded to the mean unique hue settings for the set of observers tested by Webster et al. (2000). As the spectral bandwidth varied each observer was assumed to vary the stimulus to preserve the same LvsM and SvsLM ratio. For the common environmental stimulus, observers were assumed to all choose the same broadband stimulus. This corresponded to the spectrum of a moderately saturated Munsell chip again with a chromatic angle equal to the mean unique green settings of the Webster et al. (2000) observers. As the spectral bandwidth varied each observer again had to vary the stimulus to preserve the same LvsM and SvsLM ratio. The resulting predictions are shown in Figure 1. Note that both models predict that blue and green settings should shift toward shorter wavelengths for broader spectra. However, the common ratio model predicts large increases in interobserver variations as the spectrum is broadened, while the common environmental stimulus predicts modest decreases in individual differences for broader spectra.

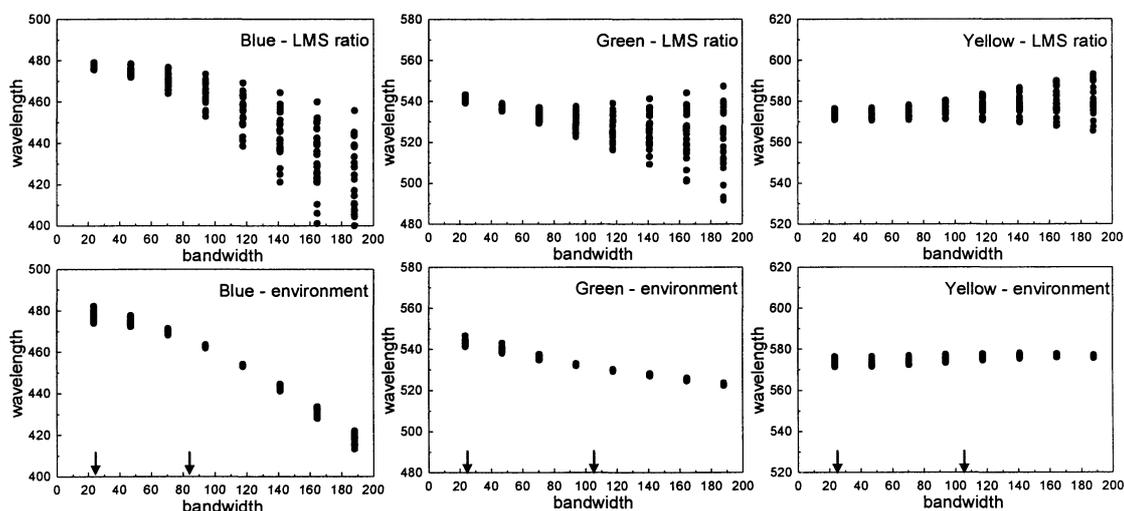


Fig. 1. Predicted individual differences in unique hues as a function of spectral bandwidth, assuming a common LMS ratio (upper) or a common environmental stimulus (lower) for unique blue, green and yellow. Arrows show bandwidths examined in the following experiments.

3. EXPERIMENT

Unique hue settings were measured with the apparatus shown in Figure 2. Light generated by a 200W Xenon lamp is collimated by a lens, L. The collimated light illuminates an interference wedge, IF, which gives a continuous spectrum that is linear in wavelength units. The light then passes through an LCD panel placed directly after the interference wedge. Spatial patterns generated on the LCD panel mask the light from different parts of IF and thus control the spectrum reaching an integrating sphere, IS, which forms a uniform 2 deg stimulus (Bonnardel et al., 1996). Subjects viewed the stimulus binocularly on a dark background in a dark room.

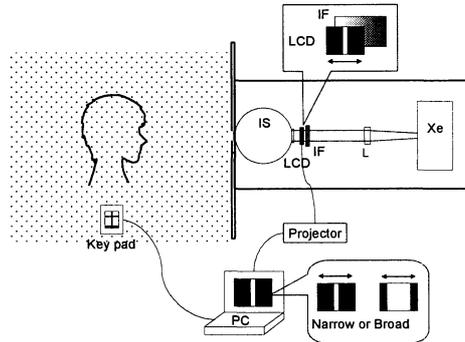


Fig. 2. Experimental apparatus. L, lens; IF, interference wedge; LCD, LCD panel; IS, integrating sphere.

Stimuli were roughly Gaussian spectral distributions.

Two different bandwidth conditions were prepared for test stimuli: 25 nm at half height for the narrow stimulus and 105 nm for broad in the case of unique green and yellow, or 85 nm in the case of unique blue. These ranges were limited by available light (at the narrow end) and spectral limits (at the broad end). The stimuli were generated by changing the slit size on the LCD panel as shown in Figure 2. The luminance of test stimuli was set near 2.0 cd/m^2 and matched for brightness to an achromatic adaptation light. Stimulus spectra were measured with a PR650 spectroradiometer.

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In the 2-deg field, the test stimulus was shown for 1.5 sec following adaptation for 30 sec to an achromatic light, and then followed again by the achromatic light. Observers used a keypad to rate the color of the test as either reddish or greenish for unique blue or yellow settings, or as yellowish or bluish for unique green. A staircase method was used to vary subsequent stimuli and the average of ten reversals was taken as the unique hue setting. Observers made unique hue settings for narrow and broad stimuli in the fovea or at 10 deg in the periphery. Each observer made six settings for each condition in random order. The same procedures were conducted for blue, green and yellow judgments. Because unique red is an extraspectral stimulus, we did not carry out measurements for red. Thirty or more subjects with normal color vision participated in the foveal fixation condition and nine of these made settings for both foveal and peripheral viewing for each unique hue condition.

4. RESULTS AND DISCUSSION

Figure 3 shows the results of unique blue, green and yellow settings for all observers on the CIE 1931 chromaticity diagram and dominant wavelength according to bandwidth of the test stimuli, respectively. These dominant wavelengths were determined with respect to CIE standard Illuminant C. Means and standard deviations are shown in the third and fourth column in Table 1. There are a number of ways in which the results deviate from the predictions of both models. First, the range of observed variation is much larger than the ranges predicted by either model we considered. This indicates that there are important factors contributing to interobserver differences that were not incorporated in the models. For example, we did not attempt to model known physiological differences such as the relative numbers of cones since these differences are not given by the Stiles and Burch color matches, nor a possible influence of rods. Moreover, we assumed that all observers would choose the same LMS ratio (for the physiological model) or the same physical stimulus (for the environmental model). The larger observed variability could suggest that these assumptions are wrong. For example, if the unique hues are learned then it is plausible to expect that observers will have different experiences and thus would learn to associate them with different stimuli. Consequently there may be no single physiological rule that is common for all observers and no environmental stimulus for which all observers would agree.

How the unique hues varied with bandwidth also differed from the predictions of both models. First, as Table 1 shows, the mean dominant wavelengths for all three hues show little systematic shift across bandwidth, in contrast to the short-wavelength shifts predicted for blue and green by either model. Second, the range of observed variation also remained similar for narrow and broadband stimuli. Thus there is no clear sign of convergence at narrower bandwidths as predicted by a fixed physiologically-defined weighting. The results also

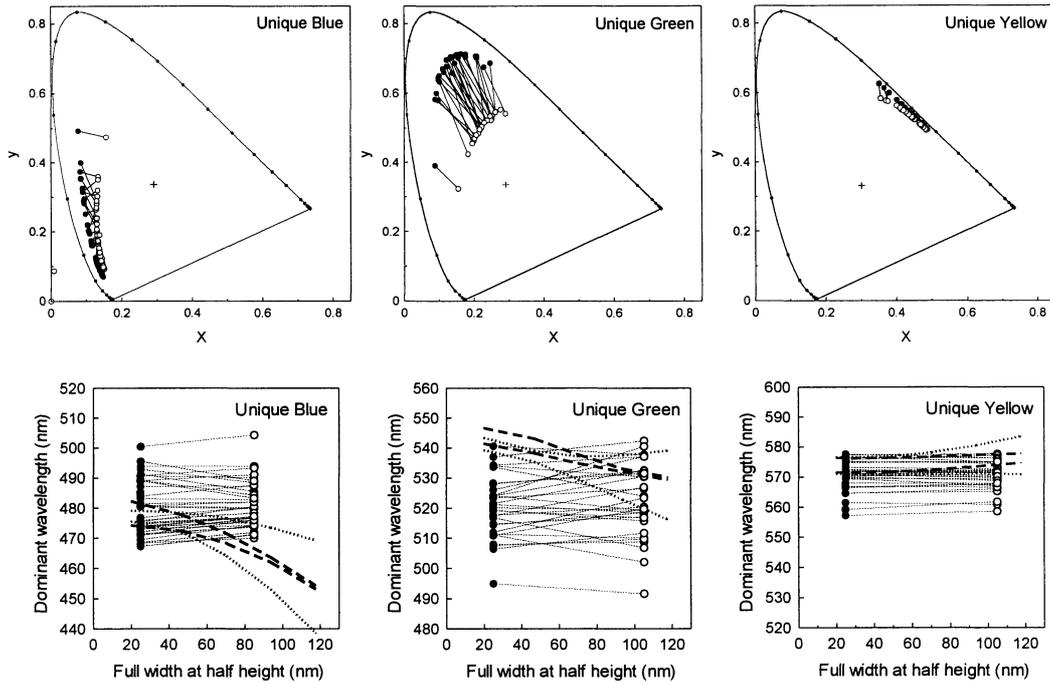


Fig. 3. Unique blue, green and red for foveally viewed stimuli shown by the CIE 1931 chromaticity coordinates (upper) and dominant wavelength (lower), respectively. Solid and open symbols indicate narrowband and broadband conditions, respectively. Crosses on chromaticity diagrams indicate the chromaticity of the achromatic adaptation. Dotted and dashed lines show the ranges of individual difference predicted by a common LMS ratio or a common environmental stimulus, respectively.

Table 1. Mean and standard deviations among subjects (dominant wavelength)

| | | Narrow (fovea) | Broad (fovea) | | Narrow (fovea) | Broad (fovea) | Narrow (peripheral) | Broad (peripheral) |
|--------|----------|----------------|---------------|---------|----------------|---------------|---------------------|--------------------|
| Blue | mean(38) | 479.44 | 480.72 | mean(8) | 475.46 | 476.79 | 472.84 | 476.57 |
| | SD(38) | 8.99 | 7.42 | SD(8) | 3.37 | 2.44 | 5.29 | 4.31 |
| Green | mean(30) | 520.05 | 521.92 | mean(9) | 520.30 | 519.33 | 512.95 | 517.66 |
| | SD(30) | 10.23 | 12.07 | SD(9) | 13.50 | 14.89 | 10.60 | 13.98 |
| Yellow | mean(33) | 570.59 | 570.68 | mean(9) | 569.40 | 569.48 | 560.42 | 561.72 |
| | SD(33) | 5.11 | 4.83 | SD(9) | 6.10 | 5.87 | 7.25 | 4.99 |

do not hint at a convergence toward a common broadband environmental stimulus, though the expected changes in this case are less pronounced.

Finally, Figure 4 also shows the average results of nine observers in both foveal and peripheral viewing conditions. Means and standard deviations are given in the right hand columns of Table 1. The effects of peripheral viewing were not consistent across observers. There was a slight overall trend for the peripheral settings to shift toward shorter wavelengths for yellow and green but not blue, a pattern roughly comparable to previous reports (Nerger et al., 1995; Volbrecht et al., 2000). However, these shifts were most evident for unique yellow, whereas the change in macular density would be expected to have larger effects on the blue and green settings. The relative stability of the hue settings at the two eccentricities is consistent with an environmental account of the unique hues, because it predicts that observers would learn to compensate for the variations in their own retinas. However, normalization for a fixed broadband color signal predicts that there should be greater constancy for the broadband stimuli. There is some suggestion of this pattern for the unique green settings, but not for blue and yellow.

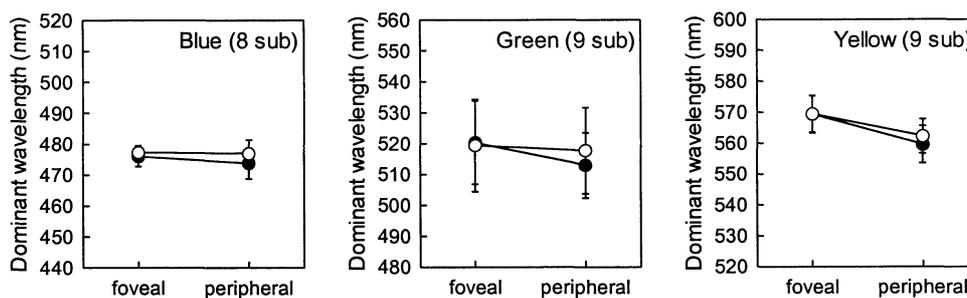


Fig. 4. Results of unique blue, green and red in foveal and peripheral condition shown dominant wavelength. Solid and open symbols indicate narrowband and broadband condition, respectively. Vertical bars show standard deviations.

In conclusion, neither of the specific models we tested adequately accounts for the observed variations in the unique hues. Both models share the assumption that changing the spectral bandwidth should require subjects to choose different stimuli in order to compensate for changes in the spectrum introduced by ocular screening pigments, but differ in the pattern these compensations take. The fact that these effects are not manifest suggests that the unique hues are relatively independent of individual differences in lens and macular pigment. Webster et al. (2000) previously found that unique hue settings between different observers could not be accounted for by differences in ocular screening, and Scheffrin and Werner (1990) showed that unique hues remain stable across the lifespan despite the fact that lens density increases with age. The current results suggest that even within a single observer at a single time, the unique hues are not closely tied to the filtering properties of their eyes. This could in part be because other factors are more important and perhaps mask this influence, or because the processes subserving color appearance already include some compensatory adjustment for the effects of screening pigments (for example, calibrating for the differences in macular density with retinal eccentricity). In either case, our results suggest that individual differences in color appearance cannot be readily traced to normal physiological variation in the spectral sensitivity of the visual system.

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