Chromatic fading following complete adaptation to unique hues

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Profound vision loss occurs after prolonged exposure to an unchanging featureless visual environment. The effect is sometimes called *visual fade*. Here we investigate this phenomenon in the color domain using two different experiments. In the first experiment we determine the time needed for a colored background to appear achromatic. Four backgrounds were tested. Each represented the observers' four unique hues. This adaptation time was compared with time to recover after adaptation Hue shifts at the end of the adaptation period were also measured. There were wide individual differences in adaptation times and recovery times. Overall recovery was faster than adaptation ($p < 0.02$). There were minimal shifts in hue. In the second experiment the changes in saturation (Munsell chroma) and lightness (Munsell value) of the background were monitored at six time intervals during the adapting process. Again asymmetric matching with Munsell samples was used. There were two distinct components to both the adaptation and recovery phases; one fast with time constant <1s, the other slow with time constant between 40 and 160s.

The experiments show that the special case of visual fade involving color represents the sensory basis for many color-related effects involving adaptation.

Introduction

It has been known for many years that perceptual fade of color and brightness occurs when observers are exposed to an expansive colored field that is otherwise featureless. A particularly dramatic version of the phenomenon occurs when the retinal image is artificially stabilized. This technique, attributed to Ditchburn & Ginsborg (1952) and Yarbus (1967), showed that the gradual fading of perception proceeds in stages, with contours disappearing first, then color, and then brightness (Gerrits & Vendrik, 1970). Interesting examples were provided by Simons, Lleras, Martinez-Conde, Slichter, Caddigan, and Nevarez (2006), who presented low-pass filtered photographs

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and instructed their subjects to fixate carefully. They referred to their effect as "scene fading." Total fading for brightness takes some time, up to several minutes in some cases, although there is marked individual variability. Similar effects are seen when an observer views a uniform surface such as a *Ganzfeld.* Brightness gradually declines to low residual levels called the Eigengrau or subjective gray (Gibson & Waddell, 1952; Gur 1989; Knau & Spillman, 1997). The characteristics of this fading have been extensively tested; it depends on the size of the field, background luminance and the amount of spatial information present (Olson, Tulunay-Keesey, & Saleh, 1993). Others have confirmed that spatial information, that is changes in luminance that give rise to contrast in an image, fades more quickly (Kelly, 1979) than brightness (Knau & Spillman, 1997).

This adaptation toward perceiving neutrality is a fundamental aspect of visual systems and is particularly important for using color information in tasks such as object detection and recognition, breaking camouflage effects, and detecting shadows. A simple example is Weber's law, which shows how sensitivity decreases with increasing background intensity. Another example is that the color of objects should remain constant under different illuminations, otherwise color would lose its value as a biological signaling mechanism. As the spectral content of natural light changes throughout the day and as we move from indoor to artificial light, the perceived chromaticity and lightness of surfaces remains largely unchanged despite the inevitable differences in reflectance spectra. The constant recomputation of (mainly) chromaticity allows all species including insects and particularly bees (Werner, Menzel, & Wehrhahn, 1988) on an almost instantaneous basis to "identify" objects of interest regardless of the diurnal shift in spectral content of daylight. This effect has been called *color constancy*, and it is attributed to Helmholtz (1867). Note that there are also substantial seasonal changes in the color of objects, driven mainly by the color shifts in vegetation (Webster, Mizokami, & Webster, 2007) In fact many experiments designed to investigate color constancy have monitored a drift toward so-called neutrality (e.g., Murray, Daugirdiene, Stanikunas, Vaitkevicius, & Kulikowski, 2006; Werner, 2014) and shown this adaptation to have a fast and slow phase. In their experiments Murray et al. (2006) compared 20° and 120° fields and showed that the 120° field revealed the dual phase adaptation and a distinct drift in the perceived background illuminant toward the neutral reference illuminant despite the physical characteristics of the background remaining constant. It should be noted that adaptation is only one of many components that contribute to so-called color constancy.

What does an observer experience when the eye is exposed to a large, temporally constant, spatially uniform (featureless) colored field? In general the area becomes achromatic and perceived brightness gradually decreases. In the historical literature there was much discussion about the rate of disappearance of the color with claims that different colors lose their saturation at different rates. Using a *Ganzfeld*, Gur (1989) provided convincing evidence that the period for complete fading is in general shorter for genuinely uniform backgrounds such as a ganzfeld, compared with those that contained some spatial information, and that blue backgrounds fade more slowly than red backgrounds.

In the present experiments we extend these findings to investigate adaptation to the four so-called unique hues, (Mollon & Jordan, 1997; Mollon, 2009; Stoughton & Conway, 2008; Valberg, 2001). Unique red and green are seen when the blue-yellow process is in equilibrium, and blue and yellow are seen when the red-green system is in equilibrium. These opposing pairs of colors, represent early (postreceptoral) color opponency and were first described by Hering (1878) and famously by Hurvich and Jameson (1955). These early postreceptoral mechanisms explain why we never experience reddish-green or bluish-yellows. Our experiments require subjects to memorize the appearance of a background, and we should mention that remembered colors are usually more saturated than they actually appeared (Bloj, Weiss, & Gegenfurtner, 2016).

Although we know that colors become desaturated (Gur, 1989) under conditions of extreme adaptation, in the present article we ask whether there is a significant shift in hue at the end of the adapting process. It is known that unique hue varies with eye color (Mollon & Jordan, 1997) and ethnic group (Webster, Webster, Bharadwaj, Verma, Jaikuma, Mada, & Vaithilingham, 2002) and according to Cicerone, Krantz, & Larimer (1975) after prolonged adaptation, an individual's unique hue undergoes a shift. Hue has also been known to shift following extended periods of daily adaptation to reveal a plastic mechanism that compensates for large individual differences in the relative differences in relative numbers L and M cones (Neitz, Carroll, Yamauchi, Neitz, & Williams, 2002). Furthermore unique hue remains unchanged at different eccentricities, whereas other hues exhibit considerable distortions when targets are viewed with the peripheral retina (Parry, McKeefry, & Murray, 2006). There is therefore compelling evidence that signals that generate unique hue sensations play a distinct role in color processing. A further test of the importance of unique hues is that they should remain unchanged under moderate adaptation conditions. If hue changed under different illuminations this would severely limit the biologic usefulness of the adaptation process. Examples might be the ability of bees to correctly identify the color of flowers and of frugivores to recognize the ripeness of fruit under evening and morning lighting conditions.

Hence, the aims of the experiments were as follows; first, to obtain quantitative data on whether there are shifts in hue induced by short term, intense adaptation conditions. Second, to investigate whether the effects are dependent on the adapting illuminant. Finally we wanted to determine the precise time course of the adapting and recovery processes.

Experiment 1. Hue shifts under different illuminants and comparison of adaptation and recovery times

Methods

Subjects

Six subjects participated in the experiments; four males (S2, S3, S4, S6) and two females (S1, S5). All had normal color vision when tested with the Farnsworth Munsell 100 Hue test (FM100). Three observers (S2, S5, S6) were highly experienced in performing color psychophysics experiments and were familiar with the objective of the experiments.

Apparatus

The experiments were conducted in a darkened room. Stimuli were presented in a rectangular viewing chamber of dimensions 50 x 67 x 51 cm. The inside of the chamber was painted grey (Munsell N7) (Cleland, 1937). It was uniformly illuminated by a computer controlled quadrichromatic solid-state source (LED lamp), containing four light-emitting diodes (LEDs) with peak emission at 638 nm (red), 594 nm (amber), 523 nm (green), and 441 nm (blue). The subject was seated in front of the chamber with his/her head inside the chamber, so that his/her entire visual field was occupied by the interior of the chamber. The luminous intensity of each of the four LEDs was digitally controlled with purpose-developed software running on a PC. The software allowed for any desired chromaticity to be selected.

The Farnsworth Munsell 100 hue test

The Farnsworth-Munsell 100 Hue Color Vision test (FM100) is a test of the ability to discriminate small increments in hue at a particular saturation. It is a standardized measure, based on colored cap-sorting, which has been widely used in both adults and children for many years (Farnsworth, 1957). The test contains four rows of tiles or chips of similar hues, each row representing broadly the orange/magenta, yellow/green, blue/purple and purple/magenta regions of color space arranged in trays. Each tray contains a fixed chip at either end of the color range and a series of chips each representing a small increment in hue between the two anchors. The order of the chips or tiles between the anchors is adjusted by the subject so that they follow an obvious sequence of hues between the two extreme points. The observer‘s arrangement of the hue tiles in to a progressive order represents his/her hue discrimination. Note that in the Munsell system, saturation is referred to as Chroma and lightness is referred to as Value. The system is designed to be perceptually unform. For example Munell hue is divided in to 10 equal perceptual steps of hue, and Chroma and Value are also specified in terms of perceptually equal steps (Cleland, 1937)

Stimuli

The inside of the viewing chamber was uniformly illuminated by one of the four test illuminants. The illuminants were chosen to be one of the four unique hues “red,” “yellow,” “green,” and “blue,” specific to each individual observer. To identify their unique hues, subjects were seated in front of the chamber as described above, and the inside was illuminated by neutral D65 illuminant. After 10 minutes adaptation to this light, color samples from the FM100 test were presented in the chamber. Each Munsell chip was mounted in a uniform black surround. Each of the four trays were viewed one at a time, and the subject was required to identify a chip that best represented their unique hue from each tray. The criterion for defining unique hues was that unique red should not contain any yellow or blue, unique yellow should not contain any green or red, unique green should not contain any yellow or blue and unique blue should not contain any green or red. If the subject reported that their unique hue was between two adjacent FM100 samples, interpolation between those two samples was performed. The unique hue selection procedure was performed several days before the main experiments. Each subject selected unique hues under D65 illuminant at least 5 times (maximum 10 times) and their averaged unique hue was calculated.

Chromaticity coordinates of unique hues were simulated with the LED lamp to customize the four unique hue illuminants to each subject. Hence, five illuminants were used in the experiment, the four unique hues, individualized for each observer and D65. For Experiment 1 only medium saturation illuminant (Munsell chroma 6) was used. To be compatible with previous work and to maintain the optimum operating range for the LEDs, the luminance of the background was 20 cd/m^2 for the four unique hue illuminants and for D65.

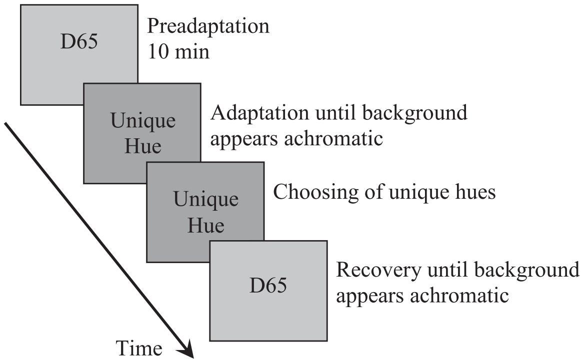

Figure 1. Stimulus presentation sequence in the first experiment. The text in the boxes represents the type of illumination. Full field unique hue adapting stimuli with Munsell chroma 6 and 20 cd/m^2 luminance appeared and remained present until the subject reported that the background color became achromatic. The time between stimulus onset and total color fade was recorded. At this point a unique hue setting was obtained using the FM100 samples. The unique hue background was then replaced by D65 and the subject reported when it appeared achromatic.

Procedure

The presentation sequence is illustrated in Figure 1. Before the experiment subjects adapted for 15 minutes in a dim room. There was a period of preadaptation for 10 minutes to the uniform N7 background under the D65 illuminant. They then adapted to one of their unique hues. They were instructed to look freely at the background allowing eye movements and report what color they see. Complete or full adaptation time was defined as the period from adapting field onset until the background appeared neutral or achromatic. When the background appeared completely achromatic, the four FM100 trays were presented one at a time on a convenient ledge within the viewing chamber. Without disturbing their adaptation the subject identified their four unique hues from these chips. The chips subtended 1.6 degrees. This process of identifying unique hue took less than 2 minutes.

After identifying their "adapted" unique hues, the chamber illuminant was switched to D65 and subjects began recovery to the neutral illuminant. During this process, subjects reported a full field afterimage, which slowly faded. The period from D65 onset to the time when the afterimage was no longer visible was defined as the recovery time. This sequence of adaptation/recovery sequence was repeated for each of the unique hues. Each subject repeated the entire sequence of measurements a minimum three times under each illuminant.

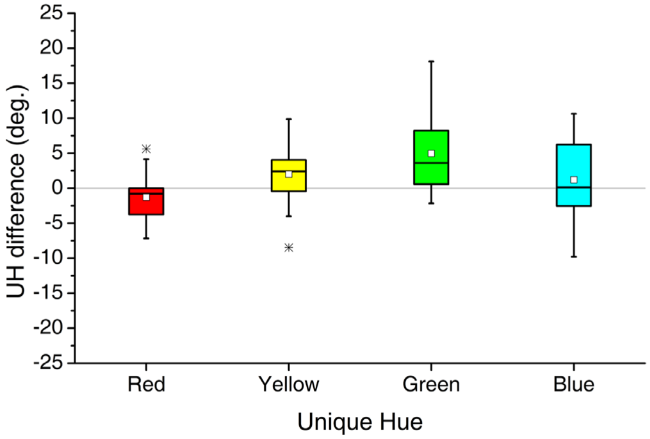

Figure 2. Unique hue changes after prolonged adaptation. Unique hue change is presented as unique hue (UH) difference in angular coordinates with respect to UH under D65. Each box and whisker represents data for one unique hue change for all observers' settings under each of the l four test illuminants. Central lines indicate the median, box edges indicate the 25th and 75th percentiles, square indicates mean and whiskers indicate 1.5x interquartile range. Outliers are plotted as asterisks.

Results

Hue shifts under different test illuminants

The first question addressed in these experiments concerned the stability of unique hue settings after prolonged adaptation. It might be expected that the perceived hue might undergo a color shift following extreme adaptation. We therefore asked observers to make unique hue settings at the conclusion of their adaptation period. To calculate the hue shifts, coordinates of FM100 samples were converted from LUV (u′v′) color space to polar color space referenced to D65. Hue is then measured as angular coordinates in a clockwise direction. Unique hue change was calculated as unique hue (UH) difference in angular coordinates with respect to D65 (UH mean difference = UH under D65 – UH after adaptation to color illuminant).

In Figure 2 we present unique hue change after prolonged adaptation for all subjects and all illuminants. In this figure there are rather wide differences in hue shift between subjects for each test illuminant and there appear to be quite substantial differences between test illuminant. To understand these effects a two-way analysis of variance was conducted with "subject" and "illuminant" as main factors. There was a significant main effect for subject and illuminant for all four test illuminants. See Table 1 for details of this analysis. However, there was a significant "interaction" term for

	Unique Red		Unique Yellow		Unique Green		Unique Blue	
Source	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Subject	F(5,107) = 32.954	<0.001	F(5,109) = 56.563	<0.001	F(5,108) = 36.419	<0.001	F(5,109) = 59.804	<0.001
Illuminant	F(4,107) = 7.637	<0.001	F(4,109) = 5.695	<0.001	F(4,108) = 7.490	<0.001	F(4,109) = 5.944	<0.001
Subject × Illuminant	F(20,107) = 1.19	0.277	F(20,109) = 1.471	0.107	F(20,108) = 2.373	0.002	F(20,109) = 1.441	0.119

Table 1. Fisher values and significance of two-way analysis of variance for differences between subject and illuminant conditions. *Note:* Sig. = Significance.

the green illuminant indicating that the two main effects were inter-dependent and we therefore conducted a post hoc analysis.

A Fisher LSD post hoc test was performed to identify significant changes in individuals' hue shifts after the adaptation. These data are presented in Table A1 in the Appendix. They show that prolonged adaptation was statistically significantly affecting unique hue stability in 25 cases out of 96 (6 subjects × 4 unique hues × 4 adapting illuminants). The most conspicuous effects were evident with the yellow illuminant (11 cases) inducing shifts in the red, yellow and green unique hue measurements. The analysis also shows that the green illuminant (six cases) induced shifts, most notably in blue hues settings, toward red. See Table A1 in the Appendix.

The primary aim of the statistical analysis was to identify any systematic effect in unique hue measurements for different test illuminants. To provide a different perspective to the statistics the shifts in unique hue setting for each observe are presented in the CIE u′v′ chromaticity plane. See Figure A1 in the Appendix. This shows unique hue settings for each of the five illuminants at maximum adaptation time. Despite some statistical effects the changes in unique hues settings were rather minimal. Hue shifts were limited to between 10° and 20° with green showing the largest effect. It is clear that the data are closely clustered around the pre-adaptation settings.

Adaptation and recovery times

In Figures 3a and 3b we illustrate the time required for the fading and the corresponding recovery phase. Although there is substantial inter-individual variability, we can see some distinct patterns in the data. Recovery times are shorter than adaptation times and adaptation takes longest for yellow which also exhibits most variance. A Wilcoxon signed-rank test confirms that adaptation time is longer than recovery time for red ($p = 0.017$), yellow ($p = 0.003$), green ($p < 0.001$), and blue ($p = 0.02$) illuminants.

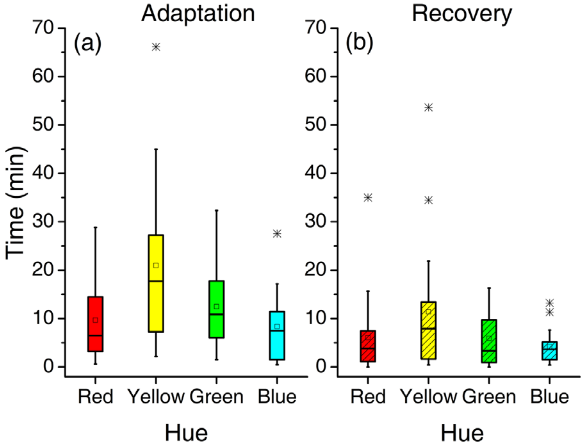

Figure 3. (a) Time for total color fade across adapting illuminants. Central lines indicate the median, box edges indicate the 25th and 75th percentiles, square indicate mean and whiskers indicate ×1.5 interquartile range. Outliers are plotted as asterisks. (b) Equivalent data for recovery times.

Illuminant	Correlation	Significance
Red	0.371	0.117
Yellow	0.518*	0.016
Green	0.72**	<0.001
Blue	0.267	0.27
All	0.555**	<0.001

Table 2. Pearson correlations between full adaptation and recovery times. *Notes:* *Correlation is significant at the 0.02 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).

There are similarities between Figures 3a and 3b that suggest there might be an association between adaptation and recovery time. This is important because although there were large individual variations we wanted to test whether this was due to a characteristic strategy adopted by certain observers. None of the observers reported employing any particular strategy during the experiments. We argue that if this were the case it would be reflected in both the adaptation and the recovery tasks. To assess this, the characteristics of the corresponding scatter plots were obtained. These data are presented in Table 2. There are two

Compared illuminants	*P* values for differences between adaptation and recovery times: Adaptation	Recovery
Red vs. Yellow	0.001	0.005
Red vs. Green	0.327	0.398
Red vs. Blue	0.872	0.904
Yellow vs. Green	0.003	0.198
Yellow vs. Blue	0.001	0.049
Green vs. Blue	0.112	0.177

Table 3. Wilcoxon signed-rank test between adaptation times of different illuminants and recovery times of different illuminants.

significant positive correlations, 0.518 for yellow and 0.72 for green. Data for the other two illuminants were more variable and correlations not significant. The association between adaptation and recovery times for all illuminants together is 0.555 ($p < 0.01$).

In the next analysis we assess the pair-wise differences between adaptation and recovery times. Mean rank adaptation time for all subjects is longest for Yellow (Wilcoxon signed-rank test, $p < 0.01$) (Figure 3a, Table 3) and as a result of this, adaptation times between yellow and the other three illuminants were significantly different. For recovery times yellow significantly different from red and blue.

Experiment 2. Chromaticity and lightness changes during the time course of adaptation

Methods

Subjects

Three subjects (S2, S5, S6) highly experienced in performing color psychophysics experiments participated in the experiments.

Apparatus and stimuli

The experiment was conducted in the same setting as in Experiment 1. The same five illuminants were used as in Experiment 1 and the same four unique hues, individualized for each observer and D65. The difference from the first experiment was that now we used six different saturations (Munsell Chroma: 2, 4, 6, 8, 10) for each color illuminant. Total illuminant variations were 20 (4 hues × 5 croma). The luminance of the background was 20 cd/m^2 for four unique hue illuminants and for D65.

Procedure

To capture the time course of the fading process, the adaptation was interrupted at five time points to allow the subjects to match the perceived intermediate chromaticity and lightness. The presentation sequence is illustrated in Figure 4. After 15 minutes' adaptation in a dim room, the subject was pre-adapted for 10 minutes to the uniform N7 background under D65 illuminant. A unique hue illuminant representing one of their unique hues was switched on and after one of the preset adaptation times the chamber illuminant was switched to D65 and subjects began recovery to the neutral illuminant. During this process, subjects reported a full field afterimage, which slowly faded. Five different saturations (Munsell Chroma: 2, 4, 6, 8, 10) and six adaptation times (0.2, 1, 5, 10, 30 and 60 seconds) for each adapting stimulus were tested in pseudorandom order. During adaptation and recovery, subjects were instructed to look freely at the background allowing eye movements and report how their perception of color changed.

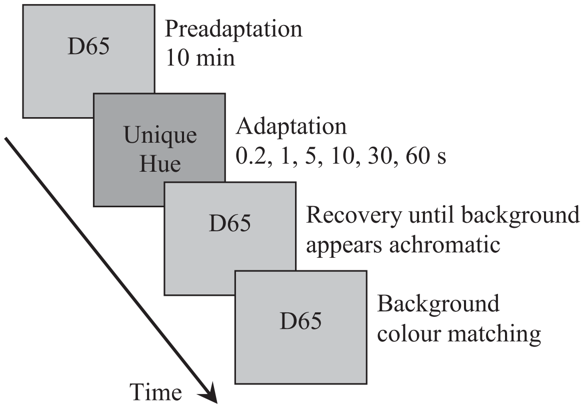

Figure 4. Stimulus presentation sequence in the second experiment. The text in the boxes represents the type of illumination. Full field unique hue stimuli with six different values of chroma (Munsell Chroma: 2, 4, 6, 8, 10) and 20 cd/m^2 luminance were presented for six adaptation times (0.2, 1, 5, 10, 30 and 60 seconds) for each adapting stimulus. After each interval D65 illuminant was switched on and the subject recovered until they reported all hue had faded and the field appeared achromatic. After recovery to D65, perceived background color at the end of adapting period was determined from their memory by matching hue, chroma and value using Munsell samples.

At the end of each of the testing periods the subjects were asked to make a hue, saturation (chroma) and lightness (value) match from their memory of the background as the adapting period was terminated. All observers performed this task easily after some practice. There was no obvious link between the hue changes and chroma and value so hue data are not included in the analysis. Note that the end of the adapting period was signaled when the unique hue illuminant was replaced by D65. Observers were instructed to prepare for this moment and to memorize the chromaticity and value immediately after the change in background was introduced. They then recovered to normal color perception before making this retrospective judgement. The Munsell Book of Colors (1600 samples; Munsell, 2000), presenting one page of a particular hue at a time was used in this matching task. Considering they were required to recall the hue, saturation (chroma) and lightness (value) having recovered to normal color perception, subjects were able to perform this task with remarkable consistency as indicated from the shapes of the adapting functions and the high correlation coefficients for the curve fitting.

Results

In the second experiment we explored the time course of the adaptation process in terms of saturation (Munsell chroma) and lightness (Munsell value). In Figure 5 the perceived change in chroma (left column) and value (right column) are illustrated for each illuminant. The effect on chroma was estimated at six different values. The solid line represents a least squares best fit of the form:

$$y = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + y_0$$

where y is chroma, t is adapting duration, A_1, and A_2 are scaling factors, τ_1 and τ_2 are time constants for the two exponential mechanisms, and y_0 is the final residual chroma level.

It is clear that there are two distinct phases to the adaptation and recovery phases. Each adapting stimulus (Figures 5a–d) has similar descending time course, but are shifted along the vertical axis starting with chroma 2 (lowest values) and finishing with chroma 10 (highest values). Chroma changes rapidly between 200 milliseconds and one second. Note that during the initial stage, chroma is increased from its physical value. This implies that observers experience an overshoot in saturation as measured from the chroma settings. Of particular interest is the fact that the lowest chroma value does not show the rapid initial phase apart from for the red illuminant.

At around 1 to 10 seconds, perception of chroma reaches its physical value (depending on adapting hue and chroma) and gradually approaches perception of chromatic neutrality. Note that although there are no error bars in Figure 5 it is apparent from the predictable changes for different levels of chroma that there is quite high consistency of performance both across this experimental variable and within subjects.

In our experiment we set y_0 as zero, because after full adaptation, the background was perceived colorless or neutral. As described above a fast mechanism operates at the initial stages of adaptation with time course independent of initial saturation (Munsell chroma). It is clear that the slower mechanism depends on saturation, because it takes more time to reach complete adaptation for the more saturated adapting illuminants. Therefore we kept τ_1 the same for each chroma value for each illuminant. See Table 4 for the fitted parameters.

The perceived lightness during adaptation exhibits the reverse function to chroma as illustrated in Figures 5e to 5h. At the initial stage lightness dimming is experienced for red, green and blue but not yellow. Interestingly this dimming effect means that, lightness is lower than the physical lightness of the background which is 20 cd/m^2. Subsequently lightness gradually increases and approaches a steady level. Perception of lightness under the yellow illuminant remains virtually unchanged with only a slight increase towards tested time of 60s. For red, green, and blue backgrounds the process of lightness perception appears to be divided in to similar fast and slow mechanisms as for chroma.

All subjects reported strong lightness dimming during switchover from D65 to the test illuminant, so the first mechanism could be attributed to fast lightness recovery from dimming. Again the sum of two exponential functions was fitted to the data. Constant τ_1 was kept the same for data with different background chroma at one background hue. For example illuminant with Red hue had 5 different conditions with chromas 2, 4, 6, 8 and 10, and for all those conditions fitting parameter τ_1 has the same value of 0.516 as shown in (Table 4). Parameter y_0 was set to 8.67 of Munsell Value. Because of the reverse symmetry between saturation and lightness perception curves, we decided to keep the same τ_1 parameter which was obtained in chroma fitting for a specific color illuminant. The fitting results are given in Table 4 and curves are plotted in Figures 5e to 5h. As can be seen in the table, excellent fits are obtained for red, green and blue illuminants with adjusted R^2 values above 0.95 for all functions apart from yellow. Perceived lightness data for the yellow illuminant is virtually unchanged throughout. Attempts to fit simple functions to these data gave quite poor results.

Discussion

Complete adaptation and recovery time

The color constancy phenomenon illustrates that adaptation towards perceiving neutrality of the ambient illuminant is important for seeing stable colors throughout the day. Previous research shows that after only one minute of full-field adaptation, illuminants gradually become more gray, that is, reduce their saturation (chroma) and finally the subjects report an

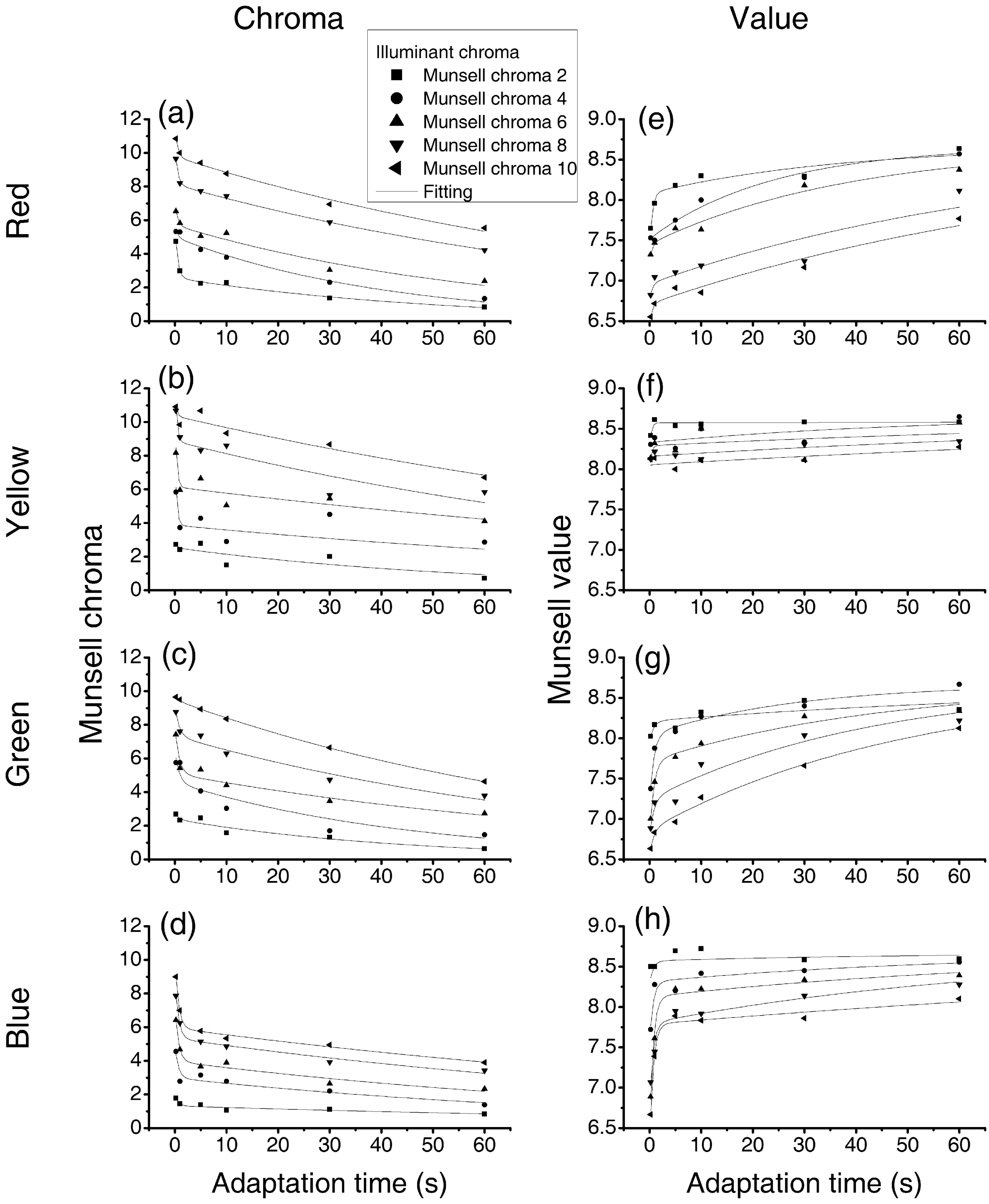

Figure 5. The time course of adaptation for Chroma and Value. Data points are mean for all observers. Each row represents adaptation to one illuminant. Different symbols code six different chroma values (Munsell chroma 2, 4, 6, 8, 10 as indicated) for each adapting hue, and the thin line represents best fit for the sum of two exponential functions.

Illuminant		Parameters for perceived chroma					Parameters for perceived lightness				
Hue	Chroma	τ_1	A_1	τ_2	A_2	Adj. R^2	τ_1	A_1	τ_2	A_2	Adj. R^2
Red	2	0.516	3.193	51.444	2.577	0.992	0.516	−0.664	37.116	−0.586	0.955
	4		0.613	40.652	5.001			−0.023	24.009	−1.148	
	6		1.246	60.521	5.708			−0.198	38.881	−1.215	
	8		2.206	92.411	8.131			−0.185	74.126	−1.708	
	10		1.622	99.284	9.779			−0.236	87.562	−1.958	
Yellow	2	0.330	0.412	59.888	2.531	0.934	0.330	−0.279	838.017	−0.097	0.595
	4		4.148	130.000	3.871			−0.038	54.949	−0.340	
	6		4.290	160.160	6.142			−0.272	118.224	−0.380	
	8		3.923	112.547	8.872			−0.056	126.782	−0.511	
	10		1.087	144.507	10.362			−0.010	161.434	−0.617	
Green	2	0.806	0.342	44.580	2.389	0.972	0.806	−0.237	88.080	−0.457	0.968
	4		1.877	46.570	4.583			−0.832	27.894	−0.630	
	6		2.794	90.259	5.091			−0.922	44.645	−0.958	
	8		1.776	81.790	7.347			−0.432	42.700	−1.432	
	10		0.265	83.607	9.480			−0.296	49.983	−1.806	
Blue	2	0.677	0.624	135.509	1.315	0.984	0.677	−0.283	50.000	−0.100	0.962
	4		1.877	88.203	2.982			−0.739	57.232	−0.359	
	6		3.294	100.869	3.969			−1.715	74.341	−0.546	
	8		3.475	121.635	5.336			−1.036	67.505	−0.872	
	10		4.172	144.436	5.947			−1.524	159.321	−0.886	

Table 4. Fitted parameters for sum of two exponential functions. Note the same values of τ_1 are used for each illuminant for both chroma and lightness recovery functions.

almost grey field. Under these conditions matching the adapted background reveals high levels of color constancy of 80% to 90% (Murray et al., 2006). It seems likely that background adaptation changes are happening in the retina and more sophisticated color constancy-like computations occur in the cortex. Here we report that prolonged full-field adaptation causes a gradual reduction in saturation (Figure 5) and after complete adaptation (Figure 3) all subjects perceived a neutral background as achromatic (chroma zero). The complete adaptation times were generally long and variable for different illuminants and individual subjects, but the overall trend was the same.

Generally, adaptation time for each illuminant is longer than recovery time as illustrated in Figure 3. There is no obvious explanation as to why recovery times are shorter than adaptation times.. The total energy (luminance) for receptor stimulation remains constant at 20cd/m^2. So receptors receive the same strength of stimulation but with opposite sign regardless of whether they are adapting or recovering. Longest adaptation times are obtained for unique yellow and shortest for blue illuminant with mean times for all subjects about 20 minutes and 10 minutes, respectively. Interestingly, there were no changes in perceived lightness for yellow, whereas lightness shifted systematically for all other illuminants.

Chromatic fading was studied with a Ganzfeld by Cohen (1958) and Gur (1989). Cohen (1958) reports that 80% of his subjects experienced red and green fields desaturation in less than three minutes, whereas the blue field was immediately experienced as gray. Conversely, Gur (1989) showed that color fading is wavelength dependent ranging from about 20 s for red to about 160 s for blue. These studies used nonunique hues, and as far as we are aware, the present work is the first investigation of extreme adaptation using individually determined unique hues. Longer and more varied adaptation times in our experiment could be explained by the fact that we had used moderate saturation (Munsell value 6) and a square viewing chamber illuminated from the top, and subjects would detect slight spatial inhomogeneities in the background. In the Ganzfeld-type experiments it was possible to produce true spatially homogenous fields. Therefore it could be that in the present experiments, small color gradient features, present in the viewing field refreshed perception as the eyes freely move over chamber walls. This could extend complete color fading times and account for the substantial interindividual variation. As mentioned above, memorizing colors increases saturation (Bloj et al., 2016), and this could induce further interindividual variability. Also, for some subjects, complete color fading was up to 1 hour in some sessions, probably because they were trying hard to maintain residual color and they were detecting the small chroma irregularities around the edges of the viewing chamber. Note that this additional variability did not induce any systematic shifts in unique hues as shown by the combination of statistical analysis and Figure A1 in the appendix, and we conclude that the results are representative of the population of color normal observers.

Stability of unique hue

Unique hues have been recognized since Hering to represent the basic color categories of red, yellow, green, and blue (for review see Abramov & Gordon, 1994). They are pure instances of hue in that they do not appear perceptually mixed with other hues. All color normal subjects seem to accept these hues as "unique" within certain constraints and research has shown that some can consistently identify unique hues of different contrast within a range of a few nanometers of dominant wavelength (Webster, Miyahara, Malkoc, Raker, 2000). Whereas previous studies noted small, but significant differences in setting both categorical hues for spectral colors (Jordan & Kulikowski, 1995; Jordan & Kulikowski, 1997) and unique hues (Mollon & Jordan, 1997; Wuerger, Atkinson, & Cropper, 2005), according to Webster at al. (2000) there are big interobserver variations in the perception of unique hues and even bigger interexperimental variability of unique hues where maximal ranges of unique blue, green and yellow overlap (for review see Kuehni, 2004). Usually, perception of unique hue is tested with a small stimulus extending a few degrees within the central visual field with short durations up to two seconds. Nagy (1979) shows that invariance or lack of invariance of unique hues with increasing intensity is dependent on stimulus duration (brief flashes of 17ms and one second were tested) with a tendency to greater hue stability for longer duration. Unique hue invariance after 5 minutes adaptation to unique hues has been tested by Cicerone et al. (1975). They used a smaller overall field size than described here and found slightly different results. Our results do not quite correspond with Cicerone et al. (1975), but our conditions are different in that we had full visual field adaptation, while they had a 2.6° adapting stimulus presented in a dark field and unique hue perception was governed by chromatic versus dark field contrast in both dark and chromatic adaptation situations. Unique hue invariance in the central versus peripheral visual field have been tested by Parry et al. (2006) who found that unique hues are invariant with retinal eccentricity (up to 24°) whereas nonunique hues undergo a shift when viewed peripherally. Unique hue changes under long-term adaptation conditions have been shown by Neitz et al. (2002). They reported that repeated adaptation to red and green illuminants (4 to 12 hours a day up to 24 days) produce changes in unique yellow perception that can last for weeks. This effect was attributed to a plastic neural mechanism that is adjustable in adults.

Here we tested stability of unique hues after complete adaptation to unique hue illuminants, with mean adapting times ranging from 8 to 22 minute and maximum time for some observers extending over an hour as seen in Figure 3a. The results show that, notwithstanding the statistical effects, overall perception of unique hues remains quite stable after complete adaptation to a particular unique hue color (Figures 2 and Figure A1). This confirms our previous observations on color constancy (Murray et al, 2006; Stanikunas, Vaitkevicius, Kulikowski, Daugirdiene, & Murray, 2005) that two separate processes are responsible for color evaluation: one is responsible for background color evaluation while the other is responding to chromatic contrast. In our case, after complete adaptation to the illuminant, the observer acquires a new neutral (gray) reference point, but unique hue perception is maintained, most likely computed from the chromatic contrast between the unique hue stimulus (Munsell chip used for the setting) and the full field background, which is physically colorful, but is perceived as a neutral field.

Time course of adaptation

In ideal cases of adaptation, it could be expected that the grey full-field background under non-neutral illumination after complete adaptation will behave like a surface under neutral illumination (here D65). The results in Figures 5a to 5d indicate that this idealized condition holds. Similar results were reported by Gur (1989) where prolonged full field adaptation to chromatic lights caused a gradual reduction in saturation. Adaptation to all unique hues shows at least two chromatic fading mechanisms having different temporal profiles. A fast mechanism with time constant <1 second and a slow mechanism with time constant between 40 and 160 seconds. Other studies also find fast and slow phases of adaptation for large but not full-field backgrounds (Fairchild & Reniff, 1995; Werner, Sharpe & Zrenner, 2000; Rinner & Gegenfurtner, 2000). Fairchild and Reniff (1995) successfully fitted the sum of two exponential functions to achromatic appearance measurements in the time course of chromatic adaptation. They used standard illuminant A, D65, D90 and a nonstandard green and a 10° × 7.5° adapting field. Their exponential time constants for the two mechanisms are approximately 1 s for the faster mechanism and 40 to 50 seconds for the slower mechanism. Our data show slightly shorter time course for the faster mechanism 0.3 to 0.8 second and similar time course for low saturated illumination for red, yellow, and green 45 to 60 seconds, whereas low saturated blue gives a time course of 135 seconds. Higher saturation requires more time to fade, therefore time constants for the slower mechanism increase to 80 to 145 seconds. Murray et al. (2006) suggested that the faster component may have a retinal origin, based perhaps in von Kries adaptation (for review see Foster, 2011) whereas the slower component is almost certainly based in the visual cortex. In general von Kries (photoreceptor-based) adaptation is considered to be faster because in the retina there is no feedback of information flow. But in the cortex there is extensive feedback (to the retina and almost certainly between different cortical areas), and this takes more processing time. This might account for the theory suggesting independent mechanisms compute background and chromatic contrast.

Gur (1989) systematically examined adaptation of various spectral colors and found that the long-wavelengths (red) had fastest adaptation times and shortest wavelengths (violet) were slowest. This is similar to our results. The slower mechanism time course is longest for blue illumination and shorter for red and green illuminations (Table 4). Rinner and Gegenfurtner (2000) explored time course of chromatic adaptation along the cardinal axes in DKL space for 64° × 46° adapting field. Their results show three components of adaptation with time constants of 20 seconds, 40 to 70 milliseconds, and faster than 10 milliseconds. Uniquely our task was designed to explore complete adaptation to unique hues and look for common mechanisms for perception of saturation (Munsell chroma) and lightness (Munsell value), we did not explore very short, or very long adaptation times in Experiment 2. Separating short and long components of adaptation seems sufficient for this study.

We successfully fitted a shorter time constant exponential function to both perceived chroma and lightness data for all unique hue illuminants except yellow. The analysis shows that fast unique hue (red, green, and blue) perception mechanisms for saturation and lightness interact strongly. It seems likely that perception of increased saturation at the beginning of the adaptation inhibits perception of lightness. Note that lightness was kept constant in the transition between D65 to the tests illuminant at 20 cd/m^2 but all observers reported an initial strong dimming for lightness before the steady, two phase increase shown in Figure 4 for all but the yellow illuminant. There is an analogous relationship between chromatic and lightness constancy, see Kulikowski, Daugirdiene, Panorgias, Stanikunas, Vaitkevicius, and Murray, 2012. The same influence on lightness "dimming" remains in the slower mechanism where gradual decrease of chroma perception appears to release inhibition of lightness.

A further aspect of our results that merits comment is lightness, sometimes called perceived luminance, during adaptation to the unique yellow illuminant. Perception of lightness slowly increases during the time course of the slower mechanism, but there is no strong dimming at 200 milliseconds, when the first data point was collected. As shown in Figure 5f, all Munsell values for different chroma illumination (chroma range from two to 10) are perceived as rather compressed—with smaller differences then the other hues. This may be caused by relative shift of yellow to higher Munsell values in chromatic space. So, observers experience an increase of yellow chroma at initial adaptation phase (Figure 5b) and chose high chroma and high value Munsell colors (Figure 5f). A similar effect was reported by Murray, Kulikowski, Stanikūnas, Vaitkevičius, and Daugirdiene (2005) in a color-matching experiment with isoluminant samples and backgrounds, when adaptation to the test illuminant was one second. A dimming effect was observed in which the subject needed to reduce the luminance of the sample to make a match. This effect was noticed for all test illuminants apart from yellow. This corresponds to our report of background lightness dimming associated with the faster mechanism for all unique hue illuminants, but yellow. Hence, in color constancy experiments for example with isoluminant samples and backgrounds under short adaptation times some subjects may not achieve a perfect match in lightness for red, green, and blue illuminants due to background lightness being reduced by the faster adaptation mechanism.

Conclusion

Our experiments have revealed that unique hues undergo small nonsystematic shifts after extreme adaptation. Although these reach statistical significance for some test illuminants and in some observers, overall they were small enough to play little or no functional role in daily life During adaptation, saturation is initially enhanced and then reduced, and lightness is first "dimmed" and then gradually increases. There are two discernible components to these two processes: one fast, the other slow. It is likely that they contribute to the stability of colors under different illuminants, described by many authors as color and lightness constancy.

Keywords: color constancy, color adaptation, unique hues, chromatic fading, large field

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Appendix

		Unique Red			Unique Yellow			Unique Green			Unique Blue		
Subject	Illuminant	Mean difference (D65-illum)	Color shift	Sig.	Mean difference (D65-illum)	Color shift	Sig.	Mean difference (D65-illum)	Color shift	Sig.	Mean difference (D65-illum)	Color shift	Sig.
S1	R	−2.16	To blue	0.399	6.72	To green	0.063	3.66	To blue	0.149	0.12	To red	0.944
S2	R	−1.81	To blue	0.318	0.87	To green	0.648	18.12**	To blue	0.001	−2.60	To green	0.055
S3	R	−1.40	To blue	0.550	0.09	To green	0.980	1.72	To blue	0.653	−9.79	To green	0.177
S4	R	−0.13	To blue	0.914	2.42	To green	0.540	0.47	To blue	0.876	−3.45	To green	0.270
S5	R	2.72	To yellow	0.360	2.99	To green	0.170	3.54	To blue	0.240	−0.23	To green	0.942
S6	R	−3.84**	To blue	0.001	7.94*	To green	0.012	0.68	To blue	0.834	0.95	To red	0.806
S1	Y	−6.95*	To blue	0.014	9.71*	To green	0.011	12.01**	To blue	<0.001	0.12	To red	0.944
S2	Y	−7.18**	To blue	0.001	4.74*	To green	0.019	16.02*	To blue	0.003	−1.57	To green	0.234
S3	Y	−3.92	To blue	0.107	0.26	To green	0.939	−0.22	To yellow	0.953	−2.50	To green	0.723
S4	Y	−1.67	To blue	0.136	3.06	To green	0.394	5.87*	To blue	0.042	7.76*	To red	0.012
S5	Y	−0.82	To blue	0.803	−0.95	To red	0.690	−0.51	To yellow	0.877	8.19*	To red	0.028
S6	Y	−5.21**	To blue	<0.001	9.88**	To green	0.001	3.30	To blue	0.264	1.59	To red	0.649
S1	G	0.77	To yellow	0.762	3.32	To green	0.337	8.27*	To blue	0.004	5.94*	To red	0.002
S2	G	0.12	To yellow	0.946	1.22	To green	0.523	8.20	To blue	0.097	0.00	No	0.999
S3	G	−3.67	To blue	0.129	−2.80	To red	0.419	−2.16	To yellow	0.571	2.50	To red	0.723
S4	G	−0.34	To blue	0.751	2.17	To green	0.543	7.81*	To blue	0.009	10.17*	To red	0.002
S5	G	4.14	To yellow	0.216	−3.00	To red	0.215	4.76	To blue	0.160	9.41*	To red	0.013
S6	G	−4.58**	To blue	<0.001	2.37	To green	0.418	4.66	To blue	0.159	6.57	To red	0.103
S1	B	−0.13	To blue	0.959	5.41	To green	0.127	2.29	To blue	0.356	−4.98*	To green	0.008
S2	B	−0.40	To blue	0.822	3.35	To green	0.089	10.69*	To blue	0.034	−2.20	To green	0.100
S3	B	−0.40	To blue	0.865	−8.49*	To red	0.022	−2.12	To yellow	0.579	−4.03	To green	0.569
S4	B	1.19	To yellow	0.329	−2.60	To red	0.511	0.20	To blue	0.947	−5.04	To green	0.115
S5	B	5.63	To yellow	0.098	−4.00	To red	0.104	10.50*	To blue	0.004	10.63*	To red	0.006
S6	B	−0.76	To blue	0.391	3.27	To green	0.220	1.69	To blue	0.561	1.22	To red	0.727

Table A1. Fisher LSD post hoc test results for the effect of illuminant on unique hue (UH). *Notes:* UH Mean difference (angular coordinate) = UH under D65 – UH after adaptation; Color shift = UH color shift direction; R = red; Y = yellow; G = green; B = blue. *The mean difference is significant at the 0.05 level. **The mean difference is significant at the 0.01 level.

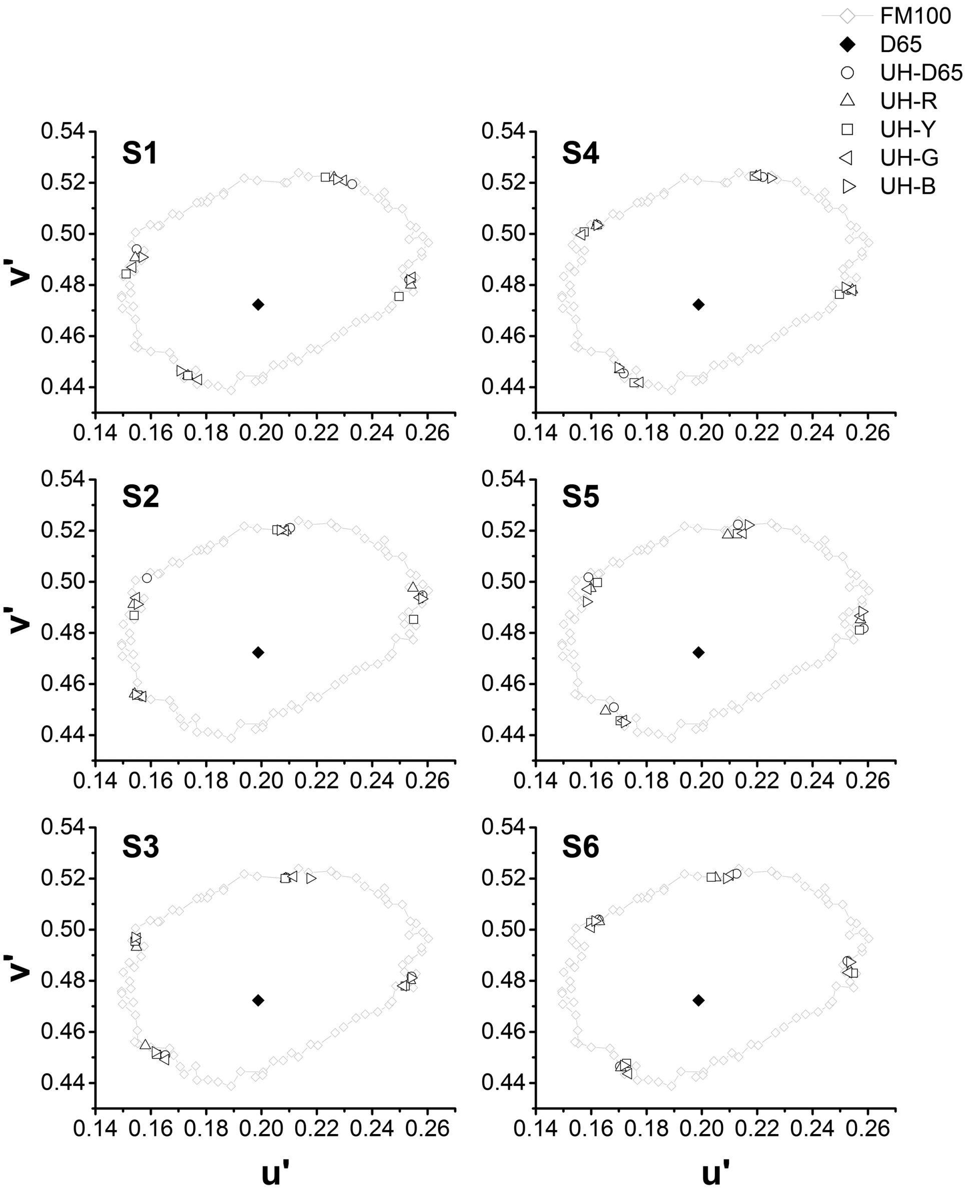

Figure A1. Unique hue settings in the CIE LUV (u′v′) chromaticity plane for six observers and for five illuminants at maximum adaptation time. Each figure represents results for one subject. Gray diamonds connected by thin lines refer to FM100 samples under D65 illuminant. Black filled diamond refers to D65 illuminant. Bold circles, top pointing triangles, squares, left pointing triangles and right pointing triangles refer to unique hue settings under D65, Red, Yellow, Green, and Blue illuminants, respectively. All unique hue settings after prolonged adaptation are plotted by corresponding FM100 sample coordinates under D65 illuminant.