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Time course of chromatic adaptation under dynamic lighting

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Abstract

Chromatic adaptation is an extensively studied concept. However, less is known about the time course of chromatic adaptation under gradually-changing lighting. Two experiments were carried out to quantify the time course of chromatic adaptation under dynamic lighting. In the first experiment, a step change in lighting chromaticity was used. The time course of adaptation was well described by the Rinner and Gegenfurtner slow adaptation exponential model [Vision Research, 40(14), 2000], and the adaptation state after saturation differed between observers. In the second experiment, chromatic adaptation was measured in response to two different speeds of lighting chromaticity transitions. An adjusted exponential model was able to fit the observed time course of adaptation for both lighting transition speeds.

Introduction

Human perception of the world is not absolute. The perceived color of an object depends on several aspects of the environment, such as the surrounding colors, the illumination and the adaptation state of the human visual system. Adaptation is known as the ability of the human visual system to adjust its sensitivity in response to illumination. The visual system has two types of photoreceptors, namely the cones and the rods. The rods mainly contribute to vision at lower light levels, whereas the cones mainly contribute to vision at higher light levels [1]. The ability of the eye to adapt to a certain illumination, therefore, depends on the characteristics of the photoreceptor that attributes to vision at that moment [2].

There are three types of adaptation: dark adaptation, light adaptation and chromatic adaptation. Dark adaptation is the recovery of visual sensitivity to dim light after being exposed to intense light. It is a well-known phenomenon and has been researched by many scientists [3][4][5]. The time course of dark adaptation can be described by a decreasing exponential function with a fast and a slow component [6]. The slow component has been found to be related to the rhodopsin concentration in the eye [7]. The fast component is believed to be related to a neural adaptation process. Light adaptation is the recovery of visual sensitivity to intense light after being exposed to dim light. When the eyes are exposed to bright light, large amounts of photopigment are broken down instantaneously due to the inability of the human eye to reduce the pupil size instantly, and as a result, rod bleaching occurs. This initial overexcitement of the photoreceptors is believed to cause glare and depending on the brightness of the exposed light, cone mediated vision is restored very rapidly. The time course of light adaptation can be described by a very rapid exponential gain change [8].

Chromatic adaptation is related to the relative sensitivities of the three types of cone receptors (L, M and S) and the corresponding opponent channels (S-(L+M), L-M and L+M) involved in color processing. Several studies have investigated the change in chromatic adaptation from daylight to incandescent lighting. Hunt [9] and Jameson et al. [10] both found that the adaptation state was about 80 - 90% after 1 min, and after 5 min the adaptation was complete. Fairchild and Reniff [11] were the first to study the time course of chromatic adaptation for other illuminations. They found that the time course of adaptation could be described by two exponential components: an extremely rapid component, with a time constant of a few seconds, and a somewhat slower component, with a time constant of almost a minute. Later, Rinner and Gegenfurtner [12] found three different components: slow (with half-life of about 20 s), fast (with half-life of about 40-70 ms), and extremely rapid (with half-life less than 10 ms). The slow and fast components are explained by photoreceptor adaptation, whereas the extremely rapid component is believed to be based on multiplicative spatial interactions in neural processing stages.

So far, chromatic adaptation has been studied under conditions where the light rapidly changes from one chromaticity to another. However, light usually changes more gradually. The current study aimed to investigate chromatic adaptation under two types of lighting conditions: a step change in chromaticity (Experiment 1) and a gradual change in chromaticity (Experiment 2). In addition to the gradual change in chromaticity (Experiment 2), the purpose of including a step change in chromaticity (Experiment 1) was to explore the variability of participants in their saturated adaptation state.

Methodology

The present study measured the time course of chromatic adaptation for dynamic lighting. Two experiments were performed with the same experimental setup. Two different kinds of stimuli were used in both experiments: color stimuli used to illuminate the walls in the room (referred to as adaptation stimuli) and color stimuli produced by a display and reflected by a small mirror (referred to as test stimuli).

Experimental Setup

The experiment took place in the Dynamic Visual Adaptation lab (DVA) in the Munsell Color Science Laboratory [13]. The DVA light lab uses 14 Philips SkyRibbon wall washing luminaires. The LED luminaires are multi-primary, comprised of red, green, blue, white, and mint-green, with 16 bits of addressable depth per channel. The intensity is controlled by high-frequency pulse-width modulation (PWM), addressed via a DMX at 40 Hz.

Figure 1. The experiment setup in the light lab, including a chin rest and keypad. In the center of the image is the mirror, subtending about 2 visual degrees, used to display test stimuli.

Inside the light lab, a display, oriented facing upward, was placed 100 cm from the back wall and centered in the lab with a distance of 190 cm to both side walls. The display was covered by a truncated black cone to prevent direct lighting from the display reaching the participant, see Figure 1. The display was slightly tilted by 5.2 degrees to improve the uniformity of the mirrored color stimuli. The display was a Dell UP2414Qt LCD with a diagonal of 60.47 cm and 56.9x5.6x33.9 cm (WxDxH) with resolution of 3840x2160 pixels. A front-surface mirror of 7.6x5.2 cm was placed 55 cm above the display oriented so that it reflected the light from the display toward the viewer. Participants were seated 149 cm from the mirror at 143 cm eye height, see Figure 1. This resulted in a square color test stimulus (reflecting 343.8x364 pixels) with a visual size of 2 degrees, surrounded by the adaptation stimulus of the wall behind it.

Software

Several Matlab programs were developed for various purposes. First, a program was created to control the stimuli shown on the display and to control the PR655 spectroradiometer used for colorimetric characterization. Second, a program was made to create a matrix and LUT model and to calculate the accuracy of the model. Next, all color rendering was done via Matlab to minimize interferences between software packages and to display the most accurate color. Finally, a special graphical user interface (GUI) was created to show the adaptation stimuli on the walls and the test stimuli on the mirror, and to record responses from participants.

Display Model

A colorimetric model of the display was used to create the most accurate test stimuli [14]. The colorimetric model was based on the characterization measured through the mirror from the observers' point of view. The primary transform matrix was determined by using the CIE 1931 XYZ values of the maximum red, maximum green and maximum blue after black correction, see Equation 1. This equation also includes an additive flare term to be added after multiplying the linear RGB with the primary transform matrix. The additive flare was made variable because it dependent on the reflected flare light that was measured off the display at each specific illumination setting. The inverse model was provided by Equation 2. The electro-optical transfer function was determined by using three one dimensional look-up tables (LUTs). The model was tested with a verification grid of colors spaced in equal steps of 40 digital counts in all three dimensions of RGB space. An excellent model fit was found, with CIEDE2000 color difference between measured and predicted colors ranging from 0.033 to 1.275 ΔE_{00}. The average color difference was 0.31 ΔE_{00} with a standard deviation of 0.250 ΔE_{00}.

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} 96.94 & 85.32 & 44.36 \\ 51.15 & 172.00 & 17.44 \\ 4.46 & 29.49 & 232.9 \end{vmatrix} \begin{vmatrix} R \\ G \\ B \end{vmatrix} + \begin{vmatrix} X_{Ill} \\ Y_{Ill} \\ Z_{Ill} \end{vmatrix} \quad (1)$$

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix} = \begin{vmatrix} 0.0138 & -0.0065 & -0.0022 \\ -0.0041 & 0.0078 & 0.0002 \\ 0.0003 & -0.0009 & 0.0043 \end{vmatrix} \left(\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} - \begin{vmatrix} X_{Ill} \\ Y_{Ill} \\ Z_{Ill} \end{vmatrix} \right) \quad (2)$$

Illumination Model

Similarly, a colorimetric model of the light lab's LED luminaires was used to illuminate the walls surrounding the mirror, see Equation 3. The electro-optical transfer function was modeled using three one dimensional look-up tables (LUTs). The CIEDE2000 color difference between measured and predicted colors in a five-dimensional grid ranged between 0.031 and 1.742 ΔE_{00}. The average color difference was 0.55 ΔE_{00} with a standard deviation of 0.222 ΔE_{00}. This model was inverted using the RGB-to-RGBW method (ignoring the M channel) [15]. The illumination model characterized the luminance of a small region of the wall just to the right of the test stimulus mirror. Despite the natural luminance falloff visible on the wall, the measured delta u'v' between this region and points within a radius of 15 visual degrees had a median of only 0.0013.

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} 205.7 & 39.32 & 98.60 & 141.1 & 133.6 \\ 94.62 & 140.6 & 40.68 & 172.7 & 131.8 \\ 0.183 & 13.84 & 589.7 & 59.16 & 80.10 \end{vmatrix} \begin{vmatrix} R \\ G \\ B \\ M \\ W \end{vmatrix} \quad (3)$$

Color Stimuli

The basic colors used to create both the adaptation stimuli on the walls and the test stimuli on the mirror corresponded to the green, blue, yellow and red stimuli of the study of Rinner and Gegenfurtner [12]; see Table 1. As they explain, the chosen stimuli represent modulations along the L-M cone axis, which was invisible to the S-cones, and the S-(L+M) cone axis, which was invisible to the L and M cones. The stimuli were taken from the Derrington-Krauskopf-Lennie (DKL) color space. The cardinal axes in the DKL color space corresponds to the S-(L+M) cone axis for 90 and 270 degrees, and L-M cone axis for 0 and 180 degrees. The -90 and 90 degrees in the vertical axis represent the L+M cone axis.

Table 1, 1976 CIE UCS color coordinates and the cone contrasts (%) of the basic colors used in the experiment

HUE	u'	v'	L	M	S
Yellow	0.1993	0.5242	-0.8	-1.1	-57.3
Blue	0.2100	0.4311	0.8	1.1	57.3
Green	0.1520	0.4795	-6.2	11.7	-0.24
Red	0.2558	0.4663	6.2	-11.7	0.24

Two isoluminant chromaticity paths were created in the u'v' chromaticity diagram by connecting the chromaticity coordinates of the yellow and blue basic colors, and those of the red and green basic colors, see Figure 2. The two chromaticity paths intersected at the gray point (0.2018 u', 0.4817 v'). The luminance of the test stimuli was constant at 40 cd/m^2 and was chosen to be 20% of the luminance of the wall measured at eye height to the right edge of the mirror, which was 200 cd/m^2.

Experiment 1: Step-Change Chromaticity

Experiment 1 Design

A within-subject design was employed to measure the time course of chromatic adaptation for four different step-change color transitions: yellow to blue, blue to yellow, red to green, and green to red. The time course of chromatic adaptation was measured with the method of adjustment.

Experiment 1 Stimuli

The adaptation stimuli consisted of the four basic colors. For the test stimuli 23 equally spaced points were taken on each of the two chromaticity paths with a Euclidean color difference between neighbouring colors of 0.0043 Δu'v' for the yellow-to-blue chromaticity path and 0.0048 Δu'v' for the green-to-red chromaticity path. These are shown as red dots in Figure 2. In addition, some stimuli beyond the red and blue basic colors were chosen; however, the yellow and green basic colors were too close to the gamut of the display to allow additional points. Three points beyond the basic colors red and blue were chosen, resulting in 26 points for each chromaticity path.

An additional 'white' adaptation stimulus of 4000 K was chosen to illuminate the room while explaining the procedure to the participants. The 4000 K white was chosen to provide a common starting point and diminish any effect of other 'white' lighting they were previously exposed to.

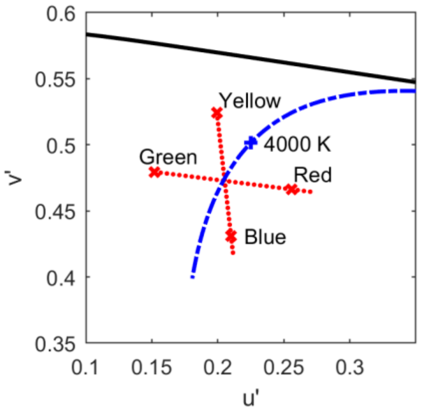

Figure 2. Stimuli chromaticity paths between yellow-blue and green-red. Dashed blue line indicates the Planckian locus. The crosses indicate the position of the basic colors, yellow, blue, green and red, and the small red dots indicate discrete stimulus colors.

Experiment 1 Procedure

Before starting the IRB-approved experiment, participants were informed about the procedure of the experiment, possible risks and harms were explained and the participants gave their written consent. After signing the consent form, participants were asked to perform the Dvorine color vision test to screen for color vision deficiencies. None of the participants had a color deficiency. Participants started the experiment with four practice trials, one for every basic color (i.e. Red, Green, Blue, and Yellow). After the participants understood the procedure, the actual experiment started.

During the experiment, the wall illumination was set to one of the basic colors, providing an adaptation stimulus. Participants were presented with a test patch and asked to adjust it until it appeared neutral (achromatic) to them by pressing either a 1 or 2 key on the keypad, indicating either an increase or decrease in steps along the corresponding chromaticity path. The method of adjustment allowed participants to alter the chromaticity of the test patch along the chromaticity path with an increase or decrease of 0.0005 in the u'v' color space. The point of neutral (achromatic) stimuli of the test patch was recorded when participants pressed the 5 key on the keypad. Between each adjustment task, the test patch turned dark for 20 seconds, and the participants were instructed to look around the test patch at the illuminated wall to encourage adaptation.

The adjustment task had to be performed at multiple times to assess the time course of adaptation, and after five minutes the adaptation stimulus was changed to a different color. All four basic colors (red, green, blue or yellow) were used as adaptation stimuli, in counter-balanced order. The goal of doing the adjustment task during the adaptation to the wall illumination was to measure the adaptation most efficiently while sampling their momentary state of adaptation without affecting the state of adaptation. The adjustment tasks were not limited in time and the amount of adjustment task performed for each base color depended on how quickly the participant made adjustments.

Experiment 1 Participants

The recruitment of participants was done in the Munsell Color Science Laboratory and Rochester Institute of Technology (i.e. employees and students). There were 8 participants who conducted the experiment: 4 females and 4 males. The participants were aged from 23 to 43 years old, with an average age of 28.5 years (SD = 7.4).

Experiment 1 Results

At each trial, participants adjusted the test patch to achromatic. The achromatic responses were recorded over time after the adaptation stimulus had changed. The achromatic responses for each of the four adaptation colors and all participants are plotted in Figure 3. The steps 26 and 4 along the two chromaticity paths correspond to either full adaptation to red, green, yellow or blue, as indicated with the cross marks in Figure 2. In figure 3, the y-axis resembles the chromaticity paths. The top left graph indicates the red-green path, the top right green-red, the bottom left yellow-blue and the bottom right blue-yellow.

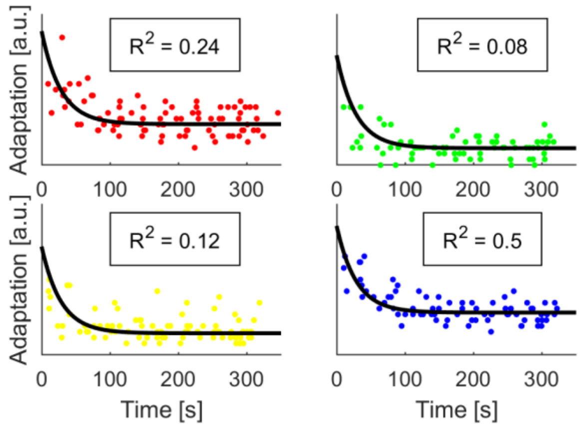

Figure 3. Achromatic responses of all participants expressed as number of steps along the two chromaticity paths for Red, Green, Yellow and Blue (from top left to bottom right figure) plotted against the time course in seconds. The solid line indicates the slow curve from the Rinner and Gegenfurtner study after normalization by the mean variation.

As can be seen in Figure 3, the achromatic responses saturated after about two minutes. The data of each adaptation color was fitted with the slow exponential decay function of Rinner and Gegenfurtner, which resulted in a low coefficient of determination (goodness of fit: R^2), as shown in Figure 3. Including any combination of the mechanisms slow, fast and/or extremely rapid resulted in a worse fit. Figure 4 presents the distributions of achromatic responses for each participant after two minutes, where we assume a saturated adaptation state. As can be seen, the mean achromatic response after two minutes of adaptation differed between participants. Moreover, participants did not fully adapt to the color of the adaptation stimulus. Each participant showed some variation in the achromatic response after two minutes. The standard deviation averaged over participants was 0.0078 Δu'v'.

Because of the individual differences in the saturated adaptation state, the data were normalized per participant by dividing the achromatic responses by the median of the achromatic responses after two minutes per adaptation color. Figure 5 shows the normalized data of all participants together. The responses after normalization were fitted with an exponential function. Figure 5 show the best possible fit (solid lines) and the function of Rinner and Gegenfurtner for the slow adaptation phase (dashed lines). By comparing Figure 3 with Figure 5 it can be seen that the data follows the curve of Rinner and Gegenfurtner somewhat better after individual normalization, but due to noise the goodness of fit is still relatively low. Both fits are difficult to assess because there are relatively few measured samples in the high-slope portion of the curve. However, the similarity in the curves gives confidence that the present results, despite differences in experimental conditions, correspond well to those in the literature.

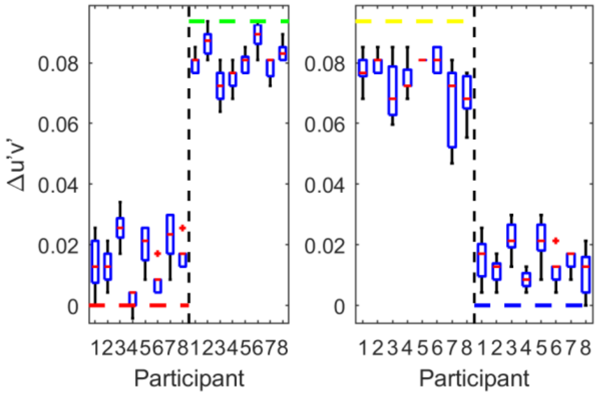

Figure 4. The boxplots of the distributions in adaptation states after two minutes of adaptation for each observer (1-8) and adaptation color plotted against the distance on the chromaticity path away from blue (for blue and yellow, right figure) or red (for red and green, left figure).

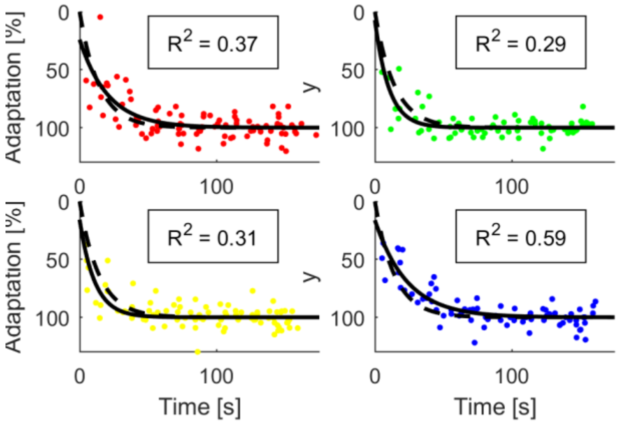

Figure 5. The time course of adaptation after individual normalization, dashed line indicating the slow curve from the Rinner and Gegenfurtner study, and the solid line is the best exponential fit through the data points for the adaptation towards red, green, yellow and blue (from top left to bottom right figure). The R^2 is indicated for the best exponential fit to the data.

Experiment 2: Dynamic Chromaticity

Experiment 2 Design

A within-subjects design was employed to measure the time course of chromatic adaptation for dynamic adaptation stimuli that gradually changes along the yellow-blue isoluminant color path from yellow to blue at two different transition durations (i.e. 30 and 60 seconds). The time course of chromatic adaptation was determined by the method of constant stimuli. Participants had to judge whether a test patch appeared yellowish or bluish at multiple time stamps during the light transition. During repeated transitions, five different test stimuli were presented at each time stamp, and psychometric curves were fitted to the responses.

Experiment 2 Stimuli

The color stimuli consisted of the same basic yellow and blue colors that were used in the first experiment. The yellow-blue path was used for both the test stimuli and the adaptation stimuli to allow for a dynamic transition in lighting with a duration of either 30 s or 60 s. The relative chromaticity of the test stimuli in relation to the lighting transition for the 30 s duration are depicted in Figure 6. The actual time period of the adaptation stimulus lighting transition including the re-adaptation was for the 30 s transition 50.7 seconds and for the 60 s transition 88.3 seconds. Those for the 60 s transition were similar, but with 18 time stamps rather than 10. At each specific time stamp, the five test stimuli were equally spaced from each other in the u'v' color space. Both transition durations were repeated five times and at each time stamp one of the randomly selected five test stimuli was presented. The chromaticities of the sets of five test stimuli at each time stamp were determined in a pilot study involving three participants and both transition durations.

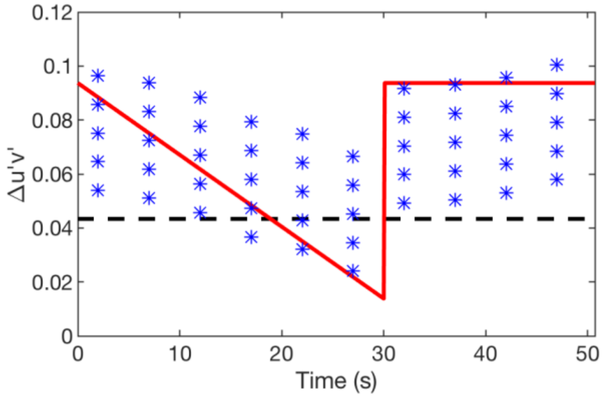

Figure 6. The stars represent the 5 chosen test stimuli at each time stamp for the 30 second condition in Δu'v' from the blue point on the blue-yellow chromaticity path, plotted against the time. The dashed line indicates the point closest to the black body locus. The solid red line indicates the change in chromaticity of the adaptation stimulus.

Experiment 2 Participants

The recruitment of participants was done in the Munsell Color Science Laboratory and Rochester Institute of Technology (i.e. employees and students). There were 21 participants that conducted the experiment: 7 female and 14 male. Among those, two were authors and 16 were students or faculty. Three persons were from outside the university. All participants had normal color vision. The participants were aged from 23 to 58 years old, with an average age of 31.1 years (SD = 10.3).

Experiment 2 Procedure

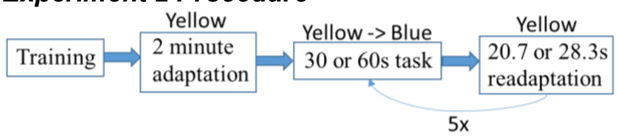

Figure 7. Schematic overview of Experiment 2

Before starting the experiment, participants who were not familiar with the procedure of the experiment received an introduction to the procedure and any further questions were resolved. During the introduction, the adaptation stimulus was set to yellow, to enable the participants to fully adapt to the illumination. After a few practice trials, the experiment started. The experiment was divided into two blocks, where the second block was a repeat of the first one. A schematic overview of the procedure is shown in Figure 7.

During the experiment, participants were asked to judge the color appearance of a test patch that was shown for half a second using a two-alternative forced choice task (2AFC): if they felt the color appearance of the test patch was yellow, they had to press the 1 on a key pad, while if it appeared to be bluish-purple

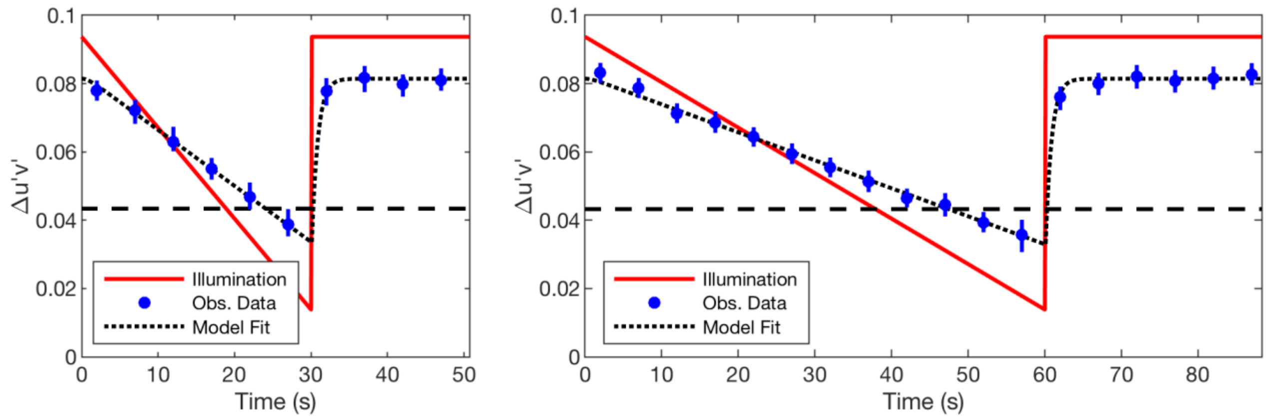

Figure 8. Achromatic point in distance from blue on the blue-yellow chromaticity path, plotted with their credible intervals at each time stamp for the 30 s (left) and 60 s (right) transitions. The adaptation stimulus (wall illumination) transitions are shown as solid red lines, and model fit as dotted black.

they had to press the 2 key. Test patches were shown every five seconds after the yellow adaptation period. During the first block, the yellow adaptation stimulus was shown for 2 minutes and then the stimulus changed gradually from yellow to blue along the yellow-blue chromaticity path. After transitioning into blue, the stimulus changed quickly back to yellow. The adaptation stimulus changed from yellow to blue over the course of either 30 or 60 seconds, after which it remained yellow during a re-adaptation period of 20.7 s or 28.3 s, respectively. The re-adaptation times were chosen based on the slow adaptation curve shape observed in Experiment 1. Between these two conditions (30 and 60 s transition times), a 30 second pause was added to readapt the participants to the yellow adaptation stimulus. The experiment consisted of several trials of a two alternative forced choice task and was repeated five times so a total of five responses were given at every time stamp by each observer.

Between the two blocks, there was an optional pause for participants to take a break before continuing. The experiment ended when all trials for each block were performed.

Experiment 2 Results

At each trial, participants gave a response which could be yellow or blue. For each combination of transition duration and time stamp, the proportion of yellow responses from all participants was determined for the set of five test stimuli and plotted against their relative distance in u'v' along the blue-yellow chromaticity path. Next, a psychometric curve was fitted to each data set across all participants.

In this study we expected that a fitted curve for determining the neutral (achromatic) point would represent a cumulative Gaussian distribution expected to reach 0.5 proportion yellow (guessing average) at the chromaticity nearest the participants' state of chromatic adaptation.

The *psignifit (v.4)* software (see: Schutt, Harmeling, Macke, and Wichmann [16]) was used to fit a psychometric curve for each duration of the light transition and time stamp, whereby the neutral (achromatic) point was indicated at the 0.5 proportion yellow responses.

Furthermore, the Wichmann and Hill method with the Monte Carlo simulation of bootstrap was considered to obtain the confidence intervals around the threshold. However, Hill [17], showed that the confidence intervals obtained by bootstrapping in the context of psychometric function estimation were too narrow. Other researchers such as Kuss et al. [18], and Fründ et al. [19], also found the confidence intervals by bootstrapping to be too narrow, therefore, in this study credible intervals according to the Bayesian statistics were calculated. With relatively small datasets, such as in this study, Bayesian statistics are more suitable and accurate [16]. The Bayesian credible intervals for the posterior distribution, based on a standard prior, were calculated according to the formula's provided by Schutt, Harmeling, Macke, and Wichmann [16].

Figure 8 shows the observed data for the determined neutral (achromatic) point with their credible intervals at each time stamps for both durations. The illumination is plotted in distance from blue on the blue-yellow chromaticity path and the dashed line in Figure 8 indicates the point closest to the black body locus. Furthermore, a model fit to the illumination and observed data is shown.

Current models of chromatic adaptation are a combination of two (Fairchild and Reniff) or three (Rinner and Gegenfurtner) exponential decay functions. Each exponential decay function can be described as in Equation 4:

$$a(t) = Ae^{-kt} \tag{4}$$

Where, $a(t)$ is the adaptation state in Δu'v' at time t, k is the time constant (related to half-life t_{50} as in $k = \ln(2) / t_{50}$), and the constant A is related to the size of the step change. When the constant A is made variable $A(t)$, this formula can be rewritten as a first-order differential equation as in Equation 5 with an initial condition as indicated by Equation 6. In these formulas only one time constant was used because any other combination of the exponential functions resulted in the other time constants to be almost zero.

$$a'(t) = k_1(a(t) - A(t)) \tag{5}$$

$$a(t_0) = A_0 \tag{6}$$

This equation was solved numerically for all $A(t)$ using the discrete step approach shown by Equation 7 (where k_1 is the time constant) with an initial condition indicated by Equation 8. To allow for an 'incomplete adaptation' offset and a good fit to the data, two constants were added as indicated by Equation 9.

$$a_1(t) = a_1(t - \Delta t) - k_1\{a_1(t - \Delta t) - A(t - \Delta t) + A_0\}\Delta t \tag{7}$$

$$a_1(t_0) = A_0 \tag{8}$$

$$a_2(t) = k_2 a_1(t) + k_3 \tag{9}$$

In Equation 9, k_3 is the 'incomplete adaptation' offset, included because participants could not fully adapt to the stimulus as also indicated in Experiment 1. Another scalar, k_2, was added to allow for the good fit of the data.

The weighted sum of root mean squared errors for both transition durations (i.e. 30 s and 60 s) together was calculated. A weighted sum was taken, because the shorter transition only contained 10 measurement points, whereas the longer had 18 measurement points. Thus, the time period of the former was weighted by 10/18. The best fit for both transition durations with an overall root mean squared error of .0016 determined by a nonlinear solver *fmincon* in MATLAB had the constants k_1=ln(2)/0.586 = 1.18, k_2=0.616 and k_3=0.0238. The constants were determined for a step size of 0.1 seconds. The dotted black lines in Figure 8 show the fitted discrete step function based on the room illumination adaptation stimulus. The discrete step function fits the data well and stays within all credible intervals. The 50.7 s time period with a 30 second transition had a R^2 value of 0.997 and the 88.3 time period with a 60 second transition had a R^2 value of 0.995.

Discussion

In this study, the time course of chromatic adaptation after a step change in the chromaticity of the illumination corresponded well to the slow adaptation curve of Rinner and Gegenfurtner. However, adaptation during a gradually changing chromaticity agreed better with the fast adaptation curve of Rinner and Gegenfurtner. In the first experiment, the method of adjustment was used to determine the achromatic stimulus, whereas the second experiment used the method of constant stimuli. This difference in methodology might explain the difference in time constant. It would, therefore, be relevant to investigate the influence of methodology on the results.

In Experiment 2, participants sometimes saw after-images when they were focusing too long on the mirror stimuli. Some participants might have judged the appearance of the test stimulus on the after-image instead of the actual test stimulus that was shown, which could have introduced additional variation in the data. To minimize the effect of after-images and the possible foveal chromatic adaptation to the test image, the images were presented only for 0.5 seconds and participants were instructed to look at the background as fast as possible after seeing the test stimulus.

In Experiment 1, some participants took a long time before submitting their first response, which might have influenced the actual response in the first few seconds. The timing of submitting a response was different between participants, which was not a problem for curve fitting, but which made it somewhat more difficult to compare the variability between participants in their saturated adaptation state.

In this study only two durations of the light transition were investigated. The results give some indication on the time course of chromatic adaptation in gradually changing dynamic lighting, although other durations should be considered for future research. Finally, the current study mainly looked at the S-cone activation for the fast adaptation track, which was believed to correspond to the local receptor adaptation, therefore, it would be interesting to investigate the time course of chromatic adaptation for different types of transitions. For example, dynamic transitions along the Planckian locus are especially relevant for lighting applications.

Conclusion

In this study, the time course of chromatic adaptation was measured for a step change in chromaticity (Experiment 1) and for a gradual change in chromaticity (Experiment 2) of the lighting in an experimental room. In Experiment 1, the time constant corresponded to the slow adaptation curve found in the study of Rinner and Gegenfurtner. The adaptation course of Experiment 2 had a good fit for a discrete step approach with three different constants: an offset, a scalar, and a time constant. The time course agreed with the fast adaptation curve of the study of Rinner and Gegenfurtner. Importantly, the model shows a good fit with the two different transition speeds, suggesting a similar overall physiological response for the time course of chromatic adaptation for temporally dynamic lighting.

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