https://doi.org/10.2352/CIC.2022.30.1.28


# Reversibility of Corresponding Colors in Sensory Chromatic Adaptation

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## Abstract

*In colorimetry and color appearance modeling it is assumed that chromatic adaptation is reversible. Recent experimental results suggest that this might not be the case and that bidirectional models of chromatic adaptation might be needed. This paper describes a series of experiments designed to collect very-high precision corresponding colors data for sensory chromatic adaptation to test the hypothesis that chromatic adaptation is reversible for individual observers. The results indicate that there are small, but statistically significant, differences in corresponding colors due to changes in the previous state of adaptation. However the effect sizes are small and the number of repeated observations required to detect these differences is very large. Thus it is concluded that these differences are, while interesting, not problematic for practical colorimetry. In addition the application of the vk20 chromatic adaptation model for predicting such effects is further explored and its 15000K reference adaptation state is validated.*

## Introduction

Chromatic adaption is broadly defined as the independent sensitivity regulation of the mechanisms of color vision in response to changes in the spectral energy distribution of the illumination (or other visual stimulus).[1] Since at least the time of Helmholtz,[2] the mechanisms of chromatic adaptation have been known to be complex and partly sensory, or automatic, and partly cognitive, or based on contextual knowledge of the stimulus.[3] Helmholtz stated that "we learn to judge how such an object would look in white light, and since our interest lies entirely in the object color we become unconscious of the sensations, on which the judgement rests",[2] which has been confirmed numerous times.[1,3] Chromatic adaptation is often considered a mechanism of so-called "color constancy" and they are sometimes referred to interchangeably. This conflagration of the two phenomena is misleading as perceptual data, as well as mathematical analyses of spectra and invariance, have illustrated that "color constancy" is neither present, nor possible, in human observers.[1,4,5] The most compelling reasons are that there are no published data showing even near-perfect color constancy and that metamerism precludes it (both samples subject to illuminant metamerism cannot be color constant when viewed in a second illumination where they do not match). Instead, it is more useful to refer to the degree of "color inconstancy" and recognize that the mechanisms of chromatic adaptation produce far less color inconstancy than would be predicted by simple radiometry and colorimetry of a scene.

Johannes von Kries[6] outlined a well-known and highly-interpreted hypothesis of the mechanism of chromatic adaptation. His concept was an extension of Grassmann's laws of additive color mixture to span stimuli perceived across changes in illumination. That set the stage for the definition of the fundamental data required to study chromatic adaptation, corresponding colors. Corresponding colors are a pair of visual stimuli, each viewed in a different viewing condition, that match in appearance. Such pairs are very rarely the same physical reflectance viewed in the two disparate viewing conditions. Thus, measuring and modeling corresponding colors becomes fundamental to quantifying and understanding chromatic adaptation as well as color inconstancy.[1]

Sensory mechanisms of chromatic adaptation are dominated by gain control in the cone photoreceptors, but it is understood that response control in other retinal cells (*i.e.*, bipolar, horizontal, amacrine, and ganglion cells) also contributes to the overall changes in color sensitivity.[7] There are almost certainly mechanisms of sensory, as well as cognitive, chromatic adaption at higher levels (*e.g.* visual cortex) of the human visual system. Cognitive mechanisms include learned interpretation of the effects of illumination on the perception of surface colors and are sometimes referred to under the umbrella term "discounting the illuminant" and can be the source of visual illusions based on misinterpretation of a stimulus configuration.[1,8] Nanay[9] discussed these cognitive mechanisms in the form of a philosophical/physiological model and Davidoff[10] explained a cognitive model of color vision. Both types of mechanisms have been clearly measured and modeled in modern color appearance models, used in a variety of practical applications, such as CIECAM02[1,11] and CAM16,[12] recently designated by the CIE as CIECAM16.

Recent work on extremely precise measurement of corresponding colors data has brought two important points to light.[13-15] The first is that there are significant individual differences in the mechanisms of adaptation in addition to differences in spectral sensitivities referred to as observer metamerism. The second is that chromatic adaptation was observed to not be reversible. In other words changes in adaptation when going from daylight to incandescent illumination were not directly offset by changes in the opposite direction during adaptation from incandescent to daylight illumination.

Possible causes of a lack in reversibility could be experimental biases or physiological mechanisms with hysteresis. The experiments reported in this paper were designed to probe this question and understand the mechanisms and significance of the observed lack of reversibility for sensory chromatic adaptation.

Cai *et al.*[14] made very precise measurements of corresponding colors and showed clear and significant lack of reversibility. However, those data are also limited by color memory issues that might confound the results such that part of

the effect is due to the experimental technique, part due to individual differences, and part due to physiological mechanisms exhibiting hysteresis. Thus, additional experimentation is required to unequivocally define the lack of reversibility in chromatic adaptation.

Fairchild[15] summarized these results, proposed a bidirectional concept of chromatic adaptation, and surveyed vision scientists on the physiological mechanisms of chromatic adaptation and the stimuli responsible for adaptation. Notably, there is no consensus in the vision science community on the critical physiological loci of chromatic adaptation (though multiple have been identified), the degree to which they might show individual variation, or the stimuli responsible for establishing the state of chromatic adaptation (*e.g.* light source, scene average, highlights, local chromaticity, long-term calibration, memory, *etc.*) Additionally, Fairchild[16] proposed and formulated a bidirectional chromatic adaptation transform, referred to as vk20, that is also evaluated further in this paper.

## Materials and Methods

All experiments were carried out using a carefully calibrated and characterized reference display (Eizo ColorEdge CG279x) driven to 10-bits per primary by a Mac Pro computer using custom MATLAB software. The colorimetric accuracy, temporal stability, and spatial uniformity of the display were all confirmed to be better than 2.0 CIE DE2000 units. The display was set to a CIE Illuminant D65 white point with a nominal luminance of 400cd/m$^2$ and DCI-P3 primaries. All experiments were completed in a darkened room. A 16-key response keyboard (with dim blue backlight illumination) was used out of the field of view to collect responses. Observers viewed the display from a distance of approximately one meter such that the individual color stimuli patches subtended a visual angle of approximately one degree. The full display (adapting background subtended approximately 18 degrees vertically and 30 degrees horizontally.

The experimental protocol involved a carefully timed sequence of adapting stimuli and test color patches from which nominal color appearance choices were made. Three adapting chromaticities were studied. In the main experiments the adapting backgrounds consisted of random 4x4 pixel luminance levels (selected from 5 levels uniformly distributed in CIE L*) of constant chromaticity. The chromaticities were that of CIE Illuminant D65 (average daylight with a CCT of 6500K) and CIE Illuminant A (typical incandescent light with a CCT of 2856K). The mean luminance of the adapting backgrounds was 20% of the maximum luminance, which was 400cd/m$^2$ for the D65 background and 241 cd/m$^2$ for the A background. In an auxiliary experiment, an adapting background (R for reference condition) that was significantly more bluish than D65, having a CCT of 15000K and maximum luminance of 246 cd/m$^2$ was utilized. The adapting backgrounds always filled the entire reference display area.

The D65-first experimental sessions consisted of first adapting for five minutes to the constant-chromaticity D65 background. During this period of adaptation, observers were entertained with a brightness-difference task that served to both reinforce the experimental task and interface and keep their gaze on the adapting background. In that task, a 4x4 grid of color samples appeared for three seconds followed by 16 seconds of the background alone (see Fig. 1). The color samples all had the same chromaticity of the background and a relative luminance of 20% of the background maximum except for one random sample of the 16 that had a relative luminance of 30%. The observer was instructed to press the key on the 16-key keypad corresponding to the brighter patch. These responses were not recorded. After the five-minute adaptation period, the cycle of actual test color stimuli began. In one cycle of stimuli, the observer select five different color stimuli. These were a neutral, and hues that appeared unique red, green, yellow, and blue (in that order). The process would begin with three seconds of the 4x4 grid of stimuli at which point the observer had to select which of the 16 stimuli was closest to the aim color. This was followed by six seconds of the adapting background. A new 4x4 grid was then presented with the color stimuli chromaticities centered on the previous choice and the increment between stimuli reduced (stimuli were always randomized in the grid). This process was repeated a total of six times until a final selection was made. Without exception, on the sixth selection all of the 16 choices appeared identical. After this process was completed for the neutral/achromatic selection, it was then repeated for each of the unique hues. After all of the selections for the D65 adaptation state were made, a five-minute period of adaptation to the A background was completed in the same manner followed by selection of the corresponding colors under illuminant A adaptation, also following the same iterative procedure. After the full cycle of adaptation to D65, selection of colors, adaptation to A, and selection of colors, an experimental session, lasting approximately 20 minutes, was complete. Observers would only complete one experimental session on any given day.

To evaluate directional effects on the state of chromatic adaptation, another set of sessions was completed with adaptation to illuminant A first, followed by adaptation to illuminant D65. The A-first experimental sessions consisted of first adapting for five minutes to the constant-chromaticity A background, selection of colors, adaptation to D65, and selection of colors. Observers never performed the D65-first and A-first sessions in a single day and always alternated between the two (one day being D65-first and then the next experimental session being A-first and so on).

For the neutral/achromatic selections, the starting 4x4 grid of stimuli were centered on the background chromaticity with increments of 0.020 in CIE u'v' to fill the square grid. The samples were then randomized and presented. The following trials were re-centered to the observer choices and the increment was reduced by a factor of 1.6 after each trial. Thus the increment for the final selection was 0.002 in u'v', which is well below the discrimination threshold for these viewing conditions. For the unique hue choices, stimuli were generated along a circle in the u'v' chromaticity diagram with a radius of 0.062 centered about the background chromaticity. The initial set of stimuli spanned a range of 141° of hue angle (360° encompassing all possible hues) centered about nominal unique hues. Succeeding trials had reduced hue ranges of 71°, 24°, 8°, 4°, and finally 1° centered on the prior observer selection. Again, all stimuli appeared identical on the last selection trial. All stimuli, for all colors, were presented at a luminance of 20% of the background maximum.

For simplicity, the four states of adaptation are summarized and notated as follows:

*Dd*: D65 adaptation when D65 was adapted to first,

*Da*: D65 adaptation when A was adapted to first,
*Ad*: A adaptation when D65 was adapted to first, and
*Aa*: A adaptation when A was adapted to first.

The fundamental question of this research is to explore whether corresponding colors under *Dd* are different from those under *Da* and similarly whether the results for *Ad* are different from those under *Aa*. Testing this hypothesis requires extremely high precision in the corresponding colors measurements and thus many replicate measurements.[13,14] Thus, the experiments were focussed on a small number of observers, two in total, each performing a large number of replications to increase precision. This is typical for exploratory vision science experiments, while not sufficient to define mean population responses as is required by industrial colorimetry. This work simply aims to determine if adaptation is reversible in any observer and whether any lack of reversibility is of practical significance.

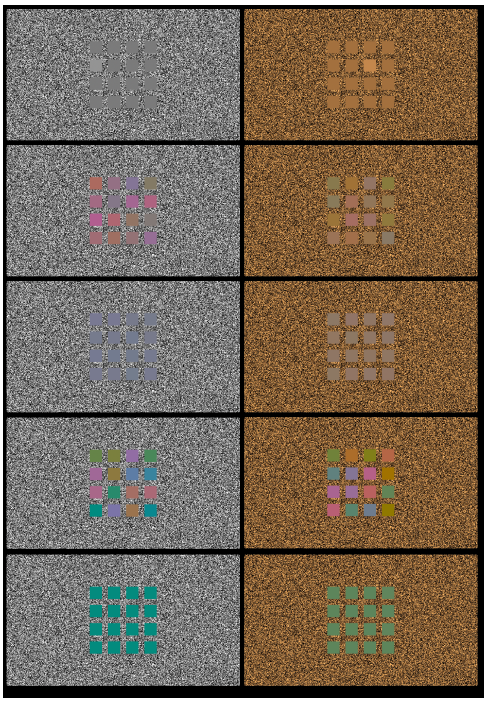

*Figure 1. Examples of visual stimuli through the experimental trials. Left column is D65 adaptation and right column is A adaptation. Row one illustrates a constant-chromaticity bright-patch identification task that was run through the five-minute adaptation period. Row two illustrates example starting trials for achromatic matching. Row three represents example ending trials for achromatic matching. Rows four and five represent example starting and ending trials for the unique green matching trials.*

The two observers who took part in the experiment have normal trichromatic color vision and extensive experience with corresponding colors experiments. Observer 1 (*OBS1*, male, 56 years old, acuity corrected to 20/20) completed 60 experimental sessions (30 with D65 adaptation first and 30 with A adaptation first) over a period of four months. Observer 2 (*OBS2*, female, 55 years old, acuity without correction of 20/20) completed eight experimental sessions (four each with D65 or A first) over a one month period. Due to the global COVID-19 pandemic during the available data collection time (March through July, 2020) no additional observers were evaluated, but there is no evidence to suggest that additional observers would impact the conclusions drawn. There is also no reason or evidence to suggest that the age of the observers has any impact on the reversibility of chromatic adaptation.

## Results

Figure 2 illustrates all of the achromatic settings for *OBS1*. The orange symbols are for the illuminant A adaptation state and cyan symbols for illuminant D65 adaptation state. Symbols outlined in yellow are for trials in which A adaptation was first (*Da* and *Aa*) and symbols outlined in blue are for trials in which D65 adaptation was first (*Dd* and *Ad*). Black triangles labelled A and D65 indicate the illuminant/adapting chromaticities. Those labelled E and R represent equal-energy and 15000K reference illuminants respectively. The black triangles labelled ND and NA represent the average neutral settings for D65- and A-first adaptation respectively.

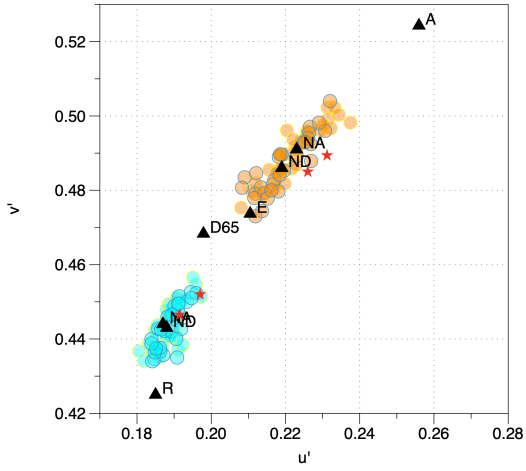


*Figure 2. Achromatic matches in CIE u'v' chromaticity for OBS1. Cyan circles represent achromatic points for D65 adaptation. Orange circles represent achromatic points for A adaptation. Points encircled in blue are for trials in which D65 adaptation occurred first. Points encircled in yellow are for trials in which A adaptation occurred first. Black triangles indicate the chromaticities for illuminants D65, A, equal energy (E) and 15000K (R) as well as the mean neutral settings for OBS1 (NA when adapting to A first and ND when adapting to D65 first.). Red stars indicate the achromatic prediction of the vK20 model.*

The first observation is that adaptation is not complete for any of the adaptation conditions as the neutral settings do not overlap the illuminant/adapting chromaticities. Both are offset toward the bluish side of the chromaticity diagram indicating that the adapting backgrounds retained some relative yellowish appearance. This is a well-known and accepted result for illuminant A adaptation,[1] but is not observed as often for D65 adaptation. In fact both observers reported that the D65 background appeared achromatic and felt they were making achromatic selections that very nearly matched the background. On the other hand the illuminant A background always retained a clear yellowish appearance.

Next, it is clear that both results for D65 adaptation, *Dd* and *Da*, are essentially identical. There is no large influence on the order of adaptation for the D65 neutral setting. There is a slight shift toward yellow when A adaptation is first, but it is not practically meaningful. For illuminant A adaptation, the D65-first mean setting (*Ad*) is shifted toward the blue from the A-first mean setting (*Aa*). The statistical significance and predictive modeling of these results are discussed below.

Figure 3 illustrates the same results for *OBS2* (with fewer replications). The general trend of the results matches those found for *OBS1* with perhaps a slightly larger mean effect for D65 adaptation and smaller effect for A adaptation. The direction of the effect is the same (order apparently matters some and the bias is in the direction of the first adapting chromaticity) and the degree of adaptation (shift from the adaptation point toward blue) is also similar for both observers.

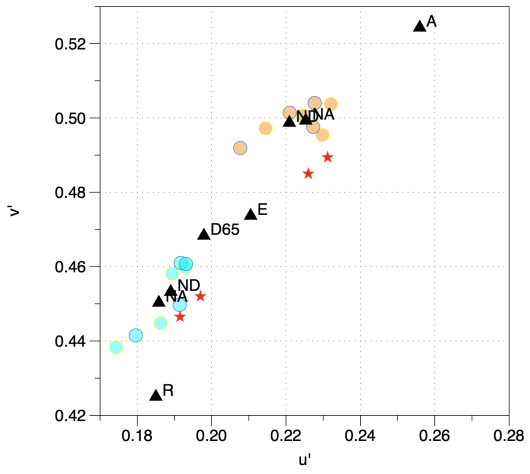


*Figure 3. The same as Fig. 2, except for OBS2.*

The unique hue data for *OBS1* and *OBS2* produced similar results. Observers only varied one dimension in the hue trials since relative saturation and luminance were fixed for all stimuli. These results indicate, as expected, that the unique hues do shift significantly for differences in adaptation state. The results also indicate that the order of adaptation does not have a significant impact. In other words the *Dd* and *Da* are very similar to one another for both observers and the *Ad* and *Aa* results are also similar to one another for both observers. Also, it is worth noting that the unique hue settings show significant inter-observer variability, which is expected.[1]

The results summarized above were also evaluated statistically. One-dimensional significance tests were performed on the u' and v' dimensions of the achromatic matches and on the u'v' hue angle (denoted as h) for the unique hue matches.

Examining the differences between matches under illuminant A adaptation and those under illuminant D65 adaptation, it is fully expected that the achromatic matches will be significantly different due to the shift in apparent achromatic point due to chromatic adaptation, but it is less predictable as to shifts in the hue angles of the unique hue matches. It has been hypothesized that, despite the impossibility of overall color constancy, hue angles might remain constant across changes in adaptation. Comparisons were made for each color match, each condition (A-first and D65-first), and for each observer. For *OBS1* all observations are significantly different. For *OBS2*, only the yellow matches are not significantly different. These results affirm the effects of chromatic adaptation that the observers have significant changes in the chromaticity coordinates of corresponding colors with the exception of the yellow unique hue for *OBS2*, which remains constant within the variability measured.

Similar analyses were made for the comparison between the two observers. In this experimental protocol, observer differences have three sources: simple observer metamerism, individual differences in the unique hues, and individual differences in the mechanisms of chromatic adaptation. All three are known sources of variability between observers and this experiment cannot separate the causes. For most of the matches, the differences between observers are significant at the $p = 0.05$ level. Exceptions are the achromatic match (Gray) under illuminant A regardless of adaptation direction, the achromatic match under illuminant D65 with D65-first, and the unique yellow under illuminant A with D65 first. Given the small number of matches with insignificant differences, four of twenty, it is safe to conclude that the corresponding colors for the two observers are indeed different.

Finally, statistical tests on order of adaptation, A-first vs. D65-first, were performed. The only matches that are significantly different with order of adaptation are the achromatic (gray), unique green, and unique blue matches for *OBS1* under illuminant A adaptation. There is a difference in the state of chromatic adaption depending on the order that adaptation occurs. However, this is only observed for *OBS1* and the significance of the results depends on the very high precision obtained by the large number of replicate measurements, 60 in this case. It is not reasonable to expect observers to evaluate color appearance, or color matches, 60 times under independent adaptation before making a judgement. In fact, most times color judgements are made on just a single set of observations. This is illustrated by the experimental results in two ways. First, there were no significant differences for *OBS2*, who made only eight replicate measurements over eight days. Second, examination of the very small effect sizes for the few significant differences shows that they have little meaning for individual color evaluations. And last, intuitive examination of the scatter of the results in Fig. 2 and 3 confirms this conclusion. While it is again established that there is a very small order effect on the measured state of chromatic adaptation, it is not large enough to be of practical concern.

## Discussion

The statistical significance of the lack of adaptation reversibility observed in this set of experiments is interesting, but it should be interpreted in the context of practical significance. While there is some measurable lack of reversibility observed, it is also unequivocally the case that it cannot be measured with single color observations, or even with the mean of small numbers of measurements. As such it is not critical for practical applications of colorimetry and color appearance models that rely on the assumption that chromatic adaptation is reversible.

This experimental work confirms that both changes in illumination (state of adaptation) and changes in observer are of

statistical and practical importance in the assessment of color appearance. However, the direction of adaptation, or the state of adaptation immediately prior to a change in adaptation state and after steady-state adaptation is achieved, is not of practical significance. One caveat of this conclusion is that these experiments were completed with simple self-luminous adapting and test stimuli. Such stimuli do not drive cognitive mechanisms of chromatic adaptation. Thus it remains a possibility that the direction, or order, of adaptation might have a significant practical impact on color appearance judgements when both sensory and cognitive mechanisms are active. This is the result previously observed by Cai *et al*.[14] that might be explained by differences in color memory for illuminated objects or directional differences in the automatic capability to discount the illuminant. The present study establishes that the cause of the previously observed bidirectionality is not within the low-level sensory mechanisms of chromatic adaptation.

Fairchild[16] proposed the vk20 model of chromatic adaptation as a straightforward and practical way to model the impacts of recent states of adaptation on color appearance. It incorporates three adapting states to set the current state of adaptation according to a modified form of the von Kries chromatic adaptation transform. These states are the intrinsic reference condition (r), the current adaptation condition (n), and the previous adaptation condition (p). In viewing situations where the previous adaptation state is known, the addition of the p coefficient can significantly improve the predictions of the adaptation model.

The vK20 model simply relies on the weighted average of three chromaticities and three degree-of-adaptation D factors (Dn, Dr, Dp) to accurately describe perceived neutral in any adapting situation and intrinsically predict any observed departures from reversibility. The full derivation of the vk20 model is given in in reference [16] and was based on historical corresponding colors data from reference [17] and [18]. The D factors estimated to predict the results of the four types of experiments in the current work were derived as follows.

Firstly, they were constrained to be positive. While negative D values are not prohibited, they do require a more complex theoretical context that has not yet been explored. Then values were selected to have consistent meaning across the four viewing conditions. For the *Dd* and *Aa* conditions, the Dp factor was set to zero since there was no known immediately preceding adaptation condition. This is essentially the same viewing conditions as in Fairchild.[16] Unfortunately the same D factors (0.7, 0.3, 0.0) did not predict the new results. For *Aa*, the factors are similar, being (0.65, 0.35, 0.0) and this difference could be accounted for by individual differences. However for *Dd*, the factors of (0.5, 0.5, 0.0) are significantly different. Historically, chromatic adaptation to D65 was considered to be complete and it is sometimes used as a reference adapting chromaticity. The D65 background did indeed appear achromatic to both observers and they were surprised that their setting consistently fell on the blue side of the adapting chromaticity rather than being a direct match. One cause of this is that both the reference condition and D65 can appear neutral in these experiments, so the 50-50 split of weighting might be reasonable.

For the conditions where the adaptation state was second in the sequence *Da* (D65 adaptation after A adaptation) and *Ad* (A adaptation after D65 adaptation), about 8% of the state of adaptation was found to depend on the previous condition. This 8% was removed from both adaptation states for the D65 adaptation (since they were equal) resulting in parameters of (0.46, 0.46, 0.08) and removed from the Dn parameter for the *Ad* adaptation since the initial D65 adaptation was offsetting full adaptation in the same colorimetric direction resulting in parameters of (0.57, 0.35, 0.08). These parameters qualitatively predict the observed trends but do not perfectly predict the results. No additional fitting or statistical analysis is warranted since the vk20 model both could predict the mean neutral results perfectly if optimized and is designed to predict population results rather than to be optimized to the results of individual observers.

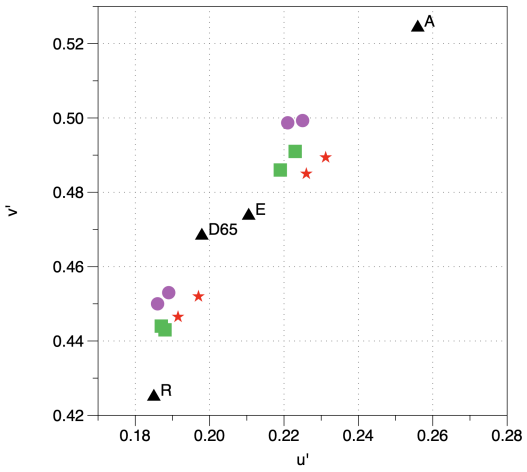


*Figure 4. Mean results and predictions for achromatic points from Figs. 4 and 5. Green squares are OBS1 and purple circles OBS2.*

Figure 4 illustrates the mean neutral settings for both observers (green symbols for *OBS1* and purple for *OBS2*) along with the vk20-predicted results (red stars, also shown on Figs. 2 and 3). The predictions shifted toward illuminant A are for A first adaptation and those shifted away are for D65-first adaptation (as are the mean experimental results). While the predictions are not perfect, they are close enough for practical colorimetry and predict the correct trend. They also clearly illustrate and predict that the equal-energy illuminant (E) and illuminant D65 (D65) reference points that are used in CIECAM02, CAM16, and other color appearance models are incorrect and corrections to those models should be considered.

Finally, it is worth returning to the question of whether 15000K is too bluish to serve as a true reference point for chromatic adaptation. Such a reference point is implicitly defined as appearing neutral itself under any reasonable viewing conditions. Since initial impressions of a 15000K adapting background are almost always that it appears significantly bluish (like sky blue), it is a reasonable question to explore. An experiment was completed using the same protocol and experimental setup and the same two observers. Only one state of adaptation was measured, the R, or reference adapting chromaticity at 15000K. Observers again adapted to the R background at 246 cd/m$^2$ for 5 minutes while selecting

luminance-difference patches from an array of samples at the same chromaticity as the background. They then completed the selection of the neutral-appearing chromaticity through the six-step iterative process. This process was then repeated six times in a session. *OBS1* completed six sessions on different days for a total of 36 neutral settings under R adaptation and *OBS2* completed two sessions on different days for a total of 12 neutral settings.

Both observers reported that the background faded from its initial bluish appearance to a completely neutral appearance well within the five-minute adaptation period. The neutral-setting results are plotted in CIE u'v' in Fig. 5 where the triangle labelled R is the adapting background and those labelled N1 and N2 are the average neutral settings for *OBS1* and *OBS2* respectively. The settings are similar for both observers and not only illustrate that the R background can be completely adapted to, but that the observers continued to select a neutral gray slightly on the blue side. This is similar to the results for D65 where the observers thought they were matching the background, but the actual selections were always more bluish. It is reasonable to assume that the reference point will vary from observer to observer and through the lifetime. Further work might be necessary to select the optimal population-wide reference chromaticity.

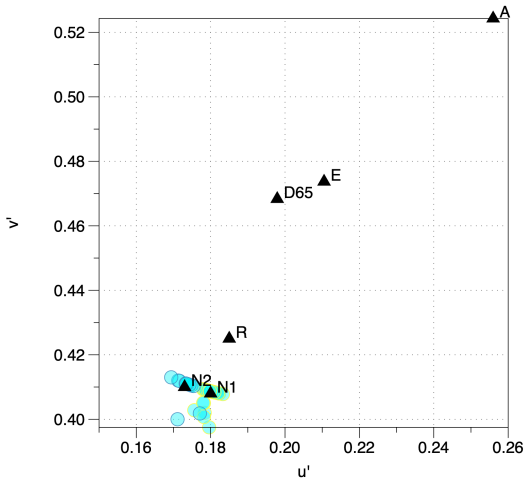


*Figure 5. Achromatic matches in CIE u'v' chromaticity for adaptation to the 15000K reference stimulus used in the vk20 model. Points encircled in yellow are for OBS1 (36 trials, mean labelled N1) while points encircled in blue are for OBS2 (12 trials, mean labelled N2).*

## Conclusions

This work was initiated to test the hypothesis that sensory chromatic adaptation is reversible. In other words, the steady state degree of adaptation does not depend on previously observed adaptation conditions.

Strictly speaking, a statistically significant difference was found in the degree of adaptation depending on the previous state of adaptation and the above hypothesis should be rejected as it was in earlier work for combinations of sensory and cognitive adaptation mechanisms (as well as color memory).

However, that statistical significance can only be measured with extreme numbers of repeat color judgements that have no practical meaning. Thus, it is concluded that the small amount a lack of reversibility in sensory chromatic adaptation is not meaningful for practical colorimetry although it might be of note in the further study of the physiological mechanisms of chromatic adaptation.

Additionally, it was illustrated that the proposed reference adaptation condition of 15000K (sky blue) is psychophysically plausible and might also depend significantly on observer age and individual differences. More detailed results and analyses for this work are available online.[19]

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