

# **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. In other words, the same sets of corresponding colors should be obtained for adaptation from daylight to incandescent light as would be obtained for adaptation from incandescent light to daylight. Recent experimental results suggest that this might not be the case and that bidirectional models of chromatic adaptation, which behave differently depending on which adaptation state comes first, 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 adaptation is broadly defined as the independent sensitivity regulation of the mechanisms of color vision.[1] Typically, chromatic adaptation is considered a response to changes in the spectral energy distribution of the illumination (or other visual stimulus) as opposed to light- and dark-adaptation, which are related phenomena of overall sensitivity regulation to the amount of stimulation, sometimes referred to as the prevailing luminance level or perceived brightness. Since at least the time of Helmholtz, [2] and almost certainly well before then, the mechanisms of chromatic adaptation have

been known to be complex and partly sensory, or automatic, and partly cognitive, or based on knowledge of the stimulus, in nature.[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] His observations of sensory and cognitive mechanisms of chromatic adaptation have been confirmed numerous times over the last century.[1,3] Chromatic adaptation is often considered a mechanism of so-called “color constancy” and they are sometimes referred to interchangeably. This conflation of the two phenomena is misleading as perceptual data, as well as mathematical analyses of spectra and invariance, have unequivocally illustrated that “color constancy” is neither present, nor possible, in human observers.[1,4,5] 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 and implemented, hypothesis of the mechanism of chromatic adaptation. His concept was essentially an extension of Grassmann’s laws of additive color mixture to span stimuli perceived across changes in illumination. This proposal by von Kries 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, viewed in different viewing conditions, that match in appearance. This is also called asymmetric color matching in contrast with normal, symmetric color matching in which two stimuli are matched in color while being viewed in identical conditions. Symmetric color matches are the basis of color matching functions, the fundamental building block of all modern systems of colorimetry. Asymmetric matches are essentially never identical with symmetric matches due to the actions of the mechanisms of chromatic adaptation that change the visual sensitivities across the two viewing conditions. Thus, measuring

and modeling corresponding colors becomes fundamental to quantifying and understanding chromatic adaptation as well as showing unequivocally that perfect “color constancy” is both impossible and not observed.[1]

Sensory mechanisms of chromatic adaptation are dominated by gain control in the cone photoreceptors, but it is also 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 adaptation, 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 sometime 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] has also discussed these cognitive mechanisms in the form of a philosophical/physiological model and Davidoff[10] has 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[1,10] and CAM16.[11]

Recent work on extremely precise measurement of corresponding colors data has brought two important points to light.[12-14] The first is that there are significant individual differences in the mechanisms of adaptation. These differences are 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.

For example, an initial test color  $\alpha$  under incandescent illumination (CIE Ill. A) is memorized. Then after adaptation to daylight illumination (CIE Ill. D65) a corresponding color is selected that matches the appearance of color  $\alpha$ . (Note that this

match will be neither a tristimulus match, nor a material match to color  $\alpha$  due to the mechanisms of chromatic adaptation.) Finally the experiment is repeated where the daylight corresponding color is memorized and then, after adaptation to incandescent illumination, a corresponding color is selected, color  $\beta$ . If color  $\alpha$  has identical tristimulus values (*i.e.* cone fundamentals) with color  $\beta$ , then chromatic adaptation is reversible. If color  $\alpha$  is not identical to color  $\beta$  then chromatic adaptation is not reversible. 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.*[13] made very precise measurements of corresponding colors in a paradigm similar to that described above and showed clear and significant lack of reversibility in chromatic adaptation (*i.e.* color  $\alpha$  was never identical with color  $\beta$ ). 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[14] 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[15] proposed and fully

formulated a bidirectional chromatic adaptation transform. That transform, referred to as vk20, is also described and 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<sup>2</sup> and DCI-P3 primaries. All experiments were completed in a darkened room. Figure 1 shows the experimental setup. The stimulus display is to the left while a dim, monochromatic control display is to the right. The control display was covered during experimental observations. Also seen in Fig. 1 is the 16-key response keyboard (with dim blue backlight illumination) that was used while 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.

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*Figure 1. Image of the experimental setup. Stimuli were presented on the calibrated reference display to the right and controlled from the black/white monitor to the left (which was covered during observations). The 16-key keypad (self-luminous in blue) was used to allow observers to select stimuli from the 4x4 array of stimuli on the experimental display without looking away. The remainder of the room was dark.*

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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<sup>2</sup> for the D65 background and 241 cd/m<sup>2</sup> for the A background. These were the maximum luminance available on the display for these chromaticities with the selected display setup. These backgrounds are illustrated in the top two panels of Fig. 2. 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<sup>2</sup> was utilized. It is illustrated in the bottom panel of Fig. 2. The adapting backgrounds always filled the entire reference display area.

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*Figure 2. Experimental background stimuli used to set the state of chromatic adaptation. Each was made up of 4x4 pixel regions randomly assigned to 5 lightness levels uniformly spaced in CIE  $L^*$  such that the mean relative luminance was at  $L^*=50$  ( $Y=20\%$ ). The top image represents the Illuminant D65 background, the middle Illuminant A, and the bottom the 15000K reference adaptation chromaticity. Peak absolute luminance were 400, 241, and 246, cd/m<sup>2</sup> respectively.*

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The D65-first experimental sessions consisted of first adapting for five minutes to the constant-chromaticity D65 background. This is significantly longer than the two-minutes generally accepted as a requirement to reach a steady state of chromatic adaptation.[1] 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. 3). 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).

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*Figure 3. 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. Note: The appearances of neutral and unique green are only valid for the viewing conditions of the experiment, and not in this illustrative figure.*

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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  $141^\circ$  of hue angle ( $360^\circ$  encompassing all possible hues) centered about nominal unique hues. Succeeding trials had reduced hue ranges of  $71^\circ$ ,  $24^\circ$ ,  $8^\circ$ ,  $4^\circ$ , and finally  $1^\circ$  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*. In other words, does the state of adaptation depend significantly on the preceding state of adaptation, or is chromatic adaptation reversible as is normally assumed in the theory and practice of color science. Testing this hypothesis requires extremely high precision in the corresponding colors measurements and thus many replicate measurements.[12,13] 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.

The two observers who took part in the experiment have normal trichromatic color vision and several decades of experience with corresponding colors experiments. They both also participated in experiments to determine degree of adaptation roughly 30 years prior to the current experiments, which was taken advantage of in the modeling process discussed below. Observer 1 (OBS1, male, 56 years old) 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) 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 it is not expected that additional observers would impact the conclusions drawn or models derived, which were established based on theory and previous results, not fits to individual observers.

## Results

Figure 4 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.

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 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.

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*Figure 4. 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 as described in the text. A total of 30 trials for each observation condition were completed.*

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Figure 5 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.

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*Figure 5. The same as Fig. 4, except for OBS2, who completed a total of 4 trials for each observation condition.*

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The unique hue data for OBS1 and OBS2 are presented in Figs. 6 and 7 respectively. Observers only varied one dimension in the hue trials since relative saturation, and of course luminance, was fixed for all stimuli. Thus the results are plotted as bar charts of the selected hue angles for each hue (red, yellow, green, blue) and adaptation state (bluish bars for D65 and yellowish bars for A adaptation). Once again the bar outlines indicate which adaptation state appeared first in the trials (blue outlines for D65-first and orange outlines for A-first).

These results indicate, as expected, that the unique hues do shift significantly for differences in adaptation state as most of the yellow bars are significantly different from the blue bars (the error bars represent 95% confidence intervals on the means). The

results also indicate that the order of adaptation does not have a significant impact as very few of the blue-outlined bars are significantly different from the yellow-outlined bars for a given state of adaptation. 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]

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*Figure 6. CIE  $u'v'$  hue angle settings for unique hues (RYGB) for OBS1. Bluish bars for D65 adaptation, yellowish for A adaptation, blue borders for D65 first, and orange borders for A first. Error bars represent plus-and-minus two standard errors. 30 trials were completed for each condition. Hue angles computed relative to the adaptation chromaticities.*

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*Figure 7. The same as Fig. 5, except for OBS2 and 4 trials for each condition. Note the significant inter-observer variability in unique hue setting.*

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The results presented 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. The results are summarized in Tables 1-3.

Table 1 examines 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 providing one dimension of constancy, hue constancy. Table 1 includes comparisons for

each color match, each condition (A-first and D65-first), and for each observer. Included are the number of observations,  $N$ , the mean differences, the standard error of the mean differences (SEM), the effect size (Cohen's  $d$ ), the  $F$  ratio, and the probability of a result due to chance ( $\text{Prob} > F$ ). In cases where the  $\text{Prob} > F$  is greater than 0.05 (a typical criterion probability), the numbers are entered in red text in the table. 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.

Table 2 presents similar analyses for the comparison between the two observers. In this experimental protocol with memory matching to internal reference colors, observer differences have three sources: simple observer metamerism (differences in spectral sensitivity), 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. The exceptions are noted in Table 2 with red  $\text{Prob} > F$  values. These 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 given the precision of this experiment.

Finally, Table 3 summarizes the statistical tests on order of adaptation, A-first vs. D65-first. This was the fundamental question motivating the present experiments. 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.

(Note that the achromatic matches are considered statistically different if either or both of the  $u'$  and  $v'$  coordinates show a significant difference.) Thus, it could be concluded that there is a difference in the state of chromatic adaptation depending on the order that adaptation occurs. However, this is only observed for OBS1 and the significance of the results is fully dependent 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. As a practical matter, this would take at least 60 days to make one color 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 (still more than any practical color judgement protocol). 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. 4 and 5 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.

Table 1. Summary of statistical tests of significance for changes in corresponding colors across change in adaptation from illuminant A to illuminant D65.

| <b>A vs. D65</b>                          | <b>N</b> | <b>Mean Difference</b> | <b>SEM Difference</b> | <b>Effect Size (Cohen's d)</b> | <b>F Ratio</b> | <b>Prob &gt; F</b> |
|---|----------|------------------------|-----------------------|--------------------------------|----------------|--------------------|
| <b>OBS1 Gray u' A-first (Aa v. Da)</b>    | 60       | 0.034                  | 0.0015                | 2.9                            | 504.3          | <0.0001            |
| <b>OBS1 Gray v' A-first (Aa v. Da)</b>    | 60       | 0.047                  | 0.00175               | 3.5                            | 717.2          | <0.0001            |
| <b>OBS1 Red h A-first (Aa v. Da)</b>      | 60       | 25.1                   | 1.38                  | 2.3                            | 331.6          | <0.0001            |
| <b>OBS1 Green h A-first (Aa v. Da)</b>    | 60       | 10.0                   | 2.05                  | 0.6                            | 23.65          | <0.0001            |
| <b>OBS1 Yellow h A-first (Aa v. Da)</b>   | 60       | 7.8                    | 1.70                  | 0.6                            | 907.1          | <0.0001            |
| <b>OBS1 Blue Red h A-first (Aa v. Da)</b> | 60       | 15.3                   | 0.64                  | 3.1                            | 565.2          | <0.0001            |
| <b>OBS1 Gray u' D65-first (Ad v. Dd)</b>  | 60       | 0.031                  | 0.0014                | 2.9                            | 488.9          | <0.0001            |
| <b>OBS1 Gray v' D65-first (Ad v. Dd)</b>  | 60       | 0.0433                 | 0.0018                | 3.1                            | 592.7          | <0.0001            |
| <b>OBS1 Red h D65-first (Ad v. Dd)</b>    | 60       | 26.7                   | 1.45                  | 2.4                            | 341.8          | <0.0001            |
| <b>OBS1 Green h D65-first (Ad v. Dd)</b>  | 60       | 12.1                   | 2.27                  | 0.7                            | 28.18          | <0.0001            |
| <b>OBS1 Yellow h D65-first (Ad v. Dd)</b> | 60       | 5.8                    | 1.73                  | 0.4                            | 11.22          | 0.0014             |
| <b>OBS1 Blue h D65-first (Ad v. Dd)</b>   | 60       | 14.7                   | 0.60                  | 3.2                            | 593.4          | <0.0001            |
| <b>OBS2 Gray u' A-first (Aa v. Da)</b>    | 8        | 0.225                  | 0.0065                | 12.2                           | 1193.7         | <0.0001            |
| <b>OBS2 Gray v' A-first (Aa v. Da)</b>    | 8        | 0.240                  | 0.0019                | 44.7                           | 15456.5        | <0.0001            |
| <b>OBS2 Red h A-first (Aa v. Da)</b>      | 8        | 27.3                   | 5.31                  | 1.8                            | 26.31          | 0.0022             |
| <b>OBS2 Green h A-first (Aa v. Da)</b>    | 8        | 32.6                   | 9.34                  | 1.2                            | 12.17          | 0.0130             |
| <b>OBS2 Yellow h A-first (Aa v. Da)</b>   | 8        | 8.6                    | 6.92                  | 0.4                            | 1.536          | 0.2629             |
| <b>OBS2 Blue h A-first (Aa v. Da)</b>     | 8        | 18.8                   | 3.62                  | 1.8                            | 27.00          | 0.0020             |
| <b>OBS2 Gray u' D65-first (Ad v. Dd)</b>  | 8        | 0.032                  | 0.0056                | 2.0                            | 32.31          | 0.0013             |
| <b>OBS2 Gray v' D65-first (Ad v. Dd)</b>  | 8        | 0.046                  | 0.0054                | 3.0                            | 71.17          | 0.0002             |
| <b>OBS2 Red h D65-first (Ad v. Dd)</b>    | 8        | 22.4                   | 6.49                  | 1.2                            | 11.89          | 0.0137             |
| <b>OBS2 Green h D65-first (Ad v. Dd)</b>  | 8        | 24.3                   | 3.83                  | 2.2                            | 40.03          | 0.0007             |
| <b>OBS2 Yellow h D65-first (Ad v. Dd)</b> | 8        | 1.85                   | 5.84                  | 0.1                            | 0.100          | 0.7621             |
| <b>OBS2 Blue h D65-first (Ad v. Dd)</b>   | 8        | 17.3                   | 2.97                  | 2.1                            | 33.82          | 0.0011             |

Table 2. Summary of statistical tests of significance for changes in corresponding colors across changes in observer, from OBS1 to OBS2.

| <b>OBS1 vs OBS2</b>         | <b>N</b> | <b>Mean Difference</b> | <b>SEM Difference</b> | <b>Effect Size (Cohen's d)</b> | <b>F Ratio</b> | <b>Prob &gt; F</b> |
|-----------------------------|----------|------------------------|-----------------------|--------------------------------|----------------|--------------------|
| A Gray u' A-first (Aa)      | 34       | 0.003                  | 0.0039                | 0.1                            | 0.396          | 0.5364             |
| A Gray v' A-first (Aa)      | 34       | 0.009                  | 0.0023                | 0.7                            | 8.480          | 0.0065             |
| A Red h A-first (Aa)        | 34       | 20.6                   | 2.74                  | 1.3                            | 56.75          | <0.0001            |
| A Green h A-first (Aa)      | 34       | 28.7                   | 2.81                  | 1.8                            | 104.4          | <0.0001            |
| A Yellow h A-first (Aa)     | 34       | 4.6                    | 4.59                  | 0.2                            | 0.990          | 0.3273             |
| A Blue h A-first (Aa)       | 34       | 11.3                   | 1.47                  | 1.3                            | 58.65          | <0.0001            |
| D65 Gray u' A-first (Da)    | 34       | 0.262                  | 0.0026                | 17.3                           | 10080          | <0.0001            |
| D65 Gray v' A-first (Da)    | 34       | 0.1848                 | 0.0030                | 10.6                           | 3675           | <0.0001            |
| D65 Red h A-first (Da)      | 34       | 22.8                   | 3.18                  | 1.2                            | 51.57          | <0.0001            |
| D65 Green h A-first (Da)    | 34       | 51.3                   | 5.81                  | 1.5                            | 77.89          | <0.0001            |
| D65 Yellow h A-first (Da)   | 34       | 5.4                    | 2.50                  | 0.4                            | 4.657          | 0.0385             |
| D65 Blue h A-first (Da)     | 34       | 7.7                    | 1.55                  | 0.9                            | 24.61          | <0.0001            |
| A Gray u' D65-first (Ad)    | 34       | 0.002                  | 0.0037                | 0.1                            | 0.1749         | 0.6786             |
| A Gray v' D65-first (Ad)    | 34       | 0.012                  | 0.0040                | 0.5                            | 9.394          | 0.0440             |
| A Red h D65-first (Ad)      | 34       | 27.9                   | 3.48                  | 1.4                            | 64.53          | <0.0001            |
| A Green D D65-first (Ad)    | 34       | 32.3                   | 2.83                  | 2.0                            | 130.37         | <0.0001            |
| A Yellow D D65-first (Ad)   | 34       | 8.0                    | 4.84                  | 0.3                            | 2.74           | 0.1076             |
| A Blue h D65-first (Ad)     | 34       | 12.7                   | 1.10                  | 2.0                            | 133.0          | <0.0001            |
| D65 Gray u' D65-first (Dd)  | 34       | 0.000                  | 0.0020                | 0.0                            | 0.0047         | 0.9455             |
| D65 Gray v' D65-first (Dd)  | 34       | 0.010                  | 0.003                 | 0.6                            | 8.975          | 0.0052             |
| D65 Red h D65-first (Dd)    | 34       | 23.6                   | 2.91                  | 1.4                            | 65.57          | <0.0001            |
| D65 Green h D65-first (Dd)  | 34       | 44.5                   | 5.77                  | 1.3                            | 59.61          | <0.0001            |
| D65 Yellow h D65-first (Dd) | 34       | 4.1                    | 1.80                  | 0.4                            | 5.125          | 0.0305             |
| D65 Blue h D65-first (Dd)   | 34       | 10.0                   | 1.59                  | 1.1                            | 29.81          | <0.0001            |

Table 3. Summary of statistical tests of significance for changes in corresponding colors across change in the order of chromatic adaptation from illuminant A-first to illuminant D65-first.

| <b><i>A-first vs. D65-first</i></b> | <b><i>N</i></b> | <b><i>Mean Difference</i></b> | <b><i>SEM Difference</i></b> | <b><i>Effect Size (Cohen's d)</i></b> | <b><i>F Ratio</i></b> | <b><i>Prob &gt; F</i></b> |
|-------------------------------------|-----------------|-------------------------------|------------------------------|---------------------------------------|-----------------------|---------------------------|
| <b>OBS1 Gray u' A (Aa v. Ad)</b>    | 60              | 0.003                         | 0.0018                       | 0.2                                   | 3.548                 | <b>0.0646</b>             |
| <b>OBS1 Gray v' A (Aa v. Ad)</b>    | 60              | 0.004                         | 0.0020                       | 0.3                                   | 4.199                 | 0.0450                    |
| <b>OBS1 Red h A (Aa v. Ad)</b>      | 60              | 2.2                           | 1.35                         | 0.2                                   | 2.731                 | <b>0.1038</b>             |
| <b>OBS1 Green h A (Aa v. Ad)</b>    | 60              | 4.0                           | 1.32                         | 0.4                                   | 9.027                 | 0.0039                    |
| <b>OBS1 Yellow h A (Aa v. Ad)</b>   | 60              | 0.7                           | 2.29                         | 0.0                                   | 0.0996                | <b>0.7534</b>             |
| <b>OBS1 Blue h A (Aa v. Ad)</b>     | 60              | 0.3                           | 0.01                         | 3.9                                   | 1847                  | <0.0001                   |
| <b>OBS1 Gray u' D65 (Da v. Dd)</b>  | 60              | 0.000                         | 0.0010                       | 0.0                                   | 0.0196                | <b>0.8892</b>             |
| <b>OBS1 Gray v' D65 (Da v. Dd)</b>  | 60              | 0.001                         | 0.0015                       | 0.1                                   | 0.1123                | <b>0.7387</b>             |
| <b>OBS1 Red h D65 (Da v. Dd)</b>    | 60              | 0.6                           | 1.47                         | 0.2                                   | 0.1591                | <b>0.6914</b>             |
| <b>OBS1 Green h D65 (Da v. Dd)</b>  | 60              | 1.9                           | 2.76                         | 0.1                                   | 0.4654                | <b>0.4978</b>             |
| <b>OBS1 Yellow h D65 (Da v. Dd)</b> | 60              | 1.3                           | 0.79                         | 0.2                                   | 2.542                 | <b>0.1163</b>             |
| <b>OBS1 Blue h D65 (Da v. Dd)</b>   | 60              | 0.5                           | 0.68                         | 0.1                                   | 0.4543                | <b>0.5030</b>             |
| <b>OBS2 Gray u' A (Aa v. Ad)</b>    | 8               | 0.004                         | 0.0061                       | 0.2                                   | 0.5044                | <b>0.5042</b>             |
| <b>OBS2 Gray v' A (Aa v. Ad)</b>    | 8               | 0.001                         | 0.0032                       | 0.1                                   | 0.0267                | <b>0.8755</b>             |
| <b>OBS2 Red h A (Aa v. Ad)</b>      | 8               | 5.1                           | 7.23                         | 0.2                                   | 0.4874                | <b>0.5112</b>             |
| <b>OBS2 Green h A (Aa v. Ad)</b>    | 8               | 0.3                           | 4.82                         | 0.0                                   | 0.0046                | <b>0.9484</b>             |
| <b>OBS2 Yellow h A (Aa v. Ad)</b>   | 8               | 4.2                           | 6.20                         | 0.2                                   | 0.4535                | <b>0.5257</b>             |
| <b>OBS2 Blue h A (Aa v. Ad)</b>     | 8               | 1.3                           | 2.95                         | 0.2                                   | 0.1938                | <b>0.6752</b>             |
| <b>OBS2 Gray u' D65 (Da v. Dd)</b>  | 8               | 0.003                         | 0.006                        | 0.2                                   | 0.3895                | <b>0.5555</b>             |
| <b>OBS2 Gray v' D65 (Da v. Dd)</b>  | 8               | 0.003                         | 0.0047                       | 0.2                                   | 0.1795                | <b>0.6865</b>             |
| <b>OBS2 Red h D65 (Da v. Dd)</b>    | 8               | 0.2                           | 4.24                         | 0.0                                   | 0.0017                | <b>0.9684</b>             |
| <b>OBS2 Green h D65 (Da v. Dd)</b>  | 8               | 8.7                           | 8.88                         | 0.3                                   | 0.9497                | <b>0.3674</b>             |
| <b>OBS2 Yellow h D65 (Da v. Dd)</b> | 8               | 2.6                           | 6.64                         | 0.1                                   | 0.1502                | <b>0.7117</b>             |
| <b>OBS2 Blue h D65 (Da v. Dd)</b>   | 8               | 2.8                           | 3.64                         | 0.3                                   | 0.5906                | <b>0.4713</b>             |

## Discussion

As outlined above, 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 in this experiment, 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, though it does indeed exist, 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 both statistically and practically important 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.*[13] 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[15] 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 and any color appearance scales built upon it. The vk20 chromatic adaptation model is expressed in Eq. 1.

$$\begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} = \begin{bmatrix} \frac{1}{(D_n L_n + D_r L_r + D_p L_p)} & 0 & 0 \\ 0 & \frac{1}{(D_n M_n + D_r M_r + D_p M_p)} & 0 \\ 0 & 0 & \frac{1}{(D_n S_n + D_r S_r + D_p S_p)} \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (1)$$

The vk20 model simply relies on three chromaticities and three degree-of-adaptation  $D$  factors to accurately describe perceived neutral in any adapting situation and intrinsically predict any observed departures from reversibility. As in the typical von Kries transformation,  $LMS$  refer to the initial cone responses and  $L_a M_a S_a$  refer to the post-adaptation cone signals.  $L_n M_n S_n$  refer to the cone responses for the adapting illuminant, however, in vk20,  $L_r M_r S_r$  refer to the responses for the reference illuminant (taken to be  $u' = 0.185$ ,  $v' = 0.425$ , approximately 15000K, sky blue) and  $L_p M_p S_p$  refer to the responses for the immediately preceding ( $p$  for “previous”) adapting illuminant.  $D_n$ ,  $D_r$ , and  $D_p$  refer to the degrees of adaptation to each of the three adapting chromaticities and must sum to 1.0.

The full derivation of the vk15 model is given in reference [15] and was based on historical corresponding colors data from reference [16] and [17]. Of note is that both OBS1 and OBS2 were participants in the original experiments that provided the data necessary to derive the model and its required three degree-of-adaptation factors. Those experiments followed a method of adjustment protocol but did have viewing conditions similar to those of the current experiments.

Fairchild[15] not only proposed the vk20 model based on previous historical research, [16,17] but evaluated its application to a variety of historical and current measurements

of corresponding colors. Those results are summarized in Table 4 along with the  $D$  factors estimated to predict the results of the four types of experiments in the current work.

Table 4. vK20 degree of adaptation coefficients for the various experiments and models described in the text. All use the  $\sim 15000\text{K}$  reference point unless indicated.

| CONDITION                    | $D_n$                  | $D_r$                       | $D_p$       |
|------------------------------|------------------------|-----------------------------|-------------|
| Fairchild [16]               | 0.7                    | 0.3                         | 0.0         |
| Hands [17]                   | 0.95                   | 0.05                        | 0.0         |
| No Hands [17]                | 0.85                   | 0.15                        | 0.0         |
| Ordinal 1 <sup>st</sup> [17] | 0.9                    | 0.1                         | 0.0         |
| Ordinal 2 <sup>nd</sup> [17] | 0.8                    | 0.1                         | 0.1         |
| Current Experiment $Dd$      | 0.5                    | 0.5                         | 0.0         |
| Current Experiment $Da$      | 0.46                   | 0.46                        | 0.08        |
| Current Experiment $Ad$      | 0.57                   | 0.35                        | 0.08        |
| Current Experiment $Aa$      | 0.65                   | 0.35                        | 0.0         |
| Ma <i>et al.</i> [18]        | $\sim 0.33$            | $\sim 0.33$                 | $\sim 0.33$ |
| Hunt & Winter [19]           | $\sim 0.6$             | $\sim 0.2$                  | $\sim 0.2$  |
| Hurvich & Jameson [20]       | 0.70                   | 0.30                        | 0.0         |
| Zhai & Luo Surface [21]      | $\sim 0.95$            | $\sim 0.05$                 | 0.0         |
| Zhai & Luo Luminous [21]     | $\sim 0.7$             | $\sim 0.3$                  | 0.0         |
| Simple von Kries             | 1.0                    | 0.0                         | 0.0         |
| CIECAM02 / CAM16             | $D$<br><i>Computed</i> | $(1-D)$<br><i>Ref. = EE</i> | 0.0         |

Current color appearance models such as CIECAM02 and CAM16, are built upon a von Kries-type chromatic adaptation transform with a single reference point, generally the equal-energy illuminant (E) but sometimes illuminant D65, and a computed degree-of-adaptation factor,  $D$  (between 0-1), to express the degree of chromatic adaptation from the reference point to the specified adaptation conditions. Implicitly in such models is a second  $D$  factor for reference chromaticity, but it is always 1- $D$ .  $D$  is a function of adapting luminance in those models. These are illustrated as an example in the bottom

row of Table 4. No previous adapting conditions are considered in these models. A simple von Kries model has an implicit  $D_n$  factor of 1.0, indicating complete chromatic adaptation, with the other two vk20 factors set to 0.0.

An advantage of the vk20 model is that it can be used to specify any state of chromatic adaptation (*i.e.*, neutral-appearing chromaticity) because it has two degrees of freedom in its three D factors. This flexibility empirically solves many problems in the prediction of chromatic adaptation states for color appearance modeling. However, the major advancement in the modeling of chromatic adaptation that remains unachieved is the development of a technique to predict the three D factors directly from measurements of the viewed scene rather than from psychophysical results collected in the viewing environment.

Different viewing conditions and observer tasks will result in different values of the three D factors. Table 4 provides examples for several published studies and the experiments reported in this paper. The Fairchild[16] data are from an extensive set of measurements of degree of chromatic adaptation illustrating that adaptation was essentially 70% complete for any adapting chromaticity relative to the 15000K (sky blue) reference condition. No  $D_p$  value is reported for that data set since the previous state of adaptation was randomized in the experiments. The next four entries in Table 4 are from further experiments reported by Fairchild[17] in which various cognitive factors were varied in the experiments and the order of adaptation was recorded and shown to have an effect. These historical results are also well-predicted with theoretically plausible D factors. The next four entries are the parameters specified for the current experimental results as described below.

Other experiments that can be well-described with the three-parameter vk20 model include the Ma *et al.*[18] recent examination of the degree of chromatic adaptation to a wide variety of adapting chromaticities, luminance levels, and spatial extent using an adjustment technique to create achromatic-appearing stimuli. In that work, adaptation

apparently depended on the adapting surround, the stimulus itself, and the reference adaptation point. Those results can also be described with the vK20 model with  $D$  parameters estimated to be approximately  $D_n = 0.33$ ,  $D_r = 0.33$ , and  $D_p = 0.33$ .

Hunt & Winter[19] measured achromatic appearance in simulated photographic reproduction situations across various adapting chromaticities along the Planckian locus. While the classic interpretation of their results is that D65 represented an approximate normalization point for adaptation, the data show that the actual point is well below the daylight locus. Their high-luminance results can be approximated using the vK20 model with  $D_n = 0.6$ ,  $D_r = 0.2$ , and  $D_p = 0.2$ .

Hurvich & Jameson[20] completed an extensive psychophysical study of white and illustrated incomplete chromatic adaptation as a function of luminance level and adapting correlated color temperature. While they had a small number of observers and significant inter-observer variation, their results can be approximated with  $D_n = 0.7$ ,  $D_r = 0.3$ , and  $D_p = 0.0$ . They also showed a small luminance dependency which could be modeled with an increase in  $D_n$  and decrease in  $D_r$  as luminance increases. Hunt and Winter[19] also showed a similar luminance dependence although they tested only two luminance levels.

Also, it is well-established historically that preferred neutrals in photographic reproductions are offset toward the blue from a true nonselective neutral. This has been reflected in historical photographic transparency and print systems as well as television standards. This history of preferred color reproduction also suggests the validity of a reference point for chromatic adaptation that is more blue than any typically encountered neutral illumination. Sky blue at 15000K fulfills that requirement. A natural question that comes up with the proposal of a 15000K reference adaptation point is whether a stimulus with such a high correlated color temperature can indeed be completely adapted to and appear neutral. A small experiment was completed, as described below, to evaluate that question.

Returning to the vk20 predictions of the current experimental results for the four different types of adaptation states,  $Dd$ ,  $Da$ ,  $Ad$ ,  $Aa$ , the D parameters that appear to reasonably describe the results are listed in Table 4. These were not statistically optimized to the data, but were instead selected to approximate the results while having theoretical consistency. 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  $D_p$  factor was set to zero since there was no known immediately preceding adaptation condition. This is essentially the same viewing conditions as in Fairchild.[15] 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  $D_n$  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 8 illustrates the mean neutral settings for both observers (green symbols for OBS1 and purple for OBS2) along with the vk20-predicted results (red stars). 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). These same predictions are also presented in Fig. 4 for reference. 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.

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*Figure 8. Mean results and predictions for achromatic points from Figs. 4 and 5. Green squares are OBS1 and purple circles OBS2.*

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Figure 9 examines the vk20 predictions of the unique hue matches. Note that only hue angle can be predicted since that is all the observers controlled in the experiment in order to avoid any need to attempt to memorize perceived saturation. Unique hues are well specified by memory (like an achromatic stimulus), but they can exist at any saturation level. Plotted are the predicted hue angles using the illuminant D65 results to predict the illuminant A corresponding colors for each observer. Two sets of predictions are included for same- and different-first adaptation. These are using the  $Dd$  results to predict  $Aa$  and then using the  $Da$  results to predict  $Ad$ . This provides a full set of

evaluations of the parameters in Table 4. Perfect predictions would all fall on the diagonal line of Fig. 9. Predictions are excellent for unique red and quite good for unique yellow and green (although large observer differences can be seen for unique yellow). The unique blue predictions are offset with both sets of predictions being lower than the observed hue angles for both observers. The cause of this discrepancy is unknown, but it could be either a problem with the model or due to the fact that the unique blue stimuli for D65 adaptation appeared very desaturated, essentially nearly neutral. There are also significant observer differences for unique blue.

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*Figure 9. Predicted as a function of observed hue angle for two combinations of D65-to-A adaptation according to the vk20 model as outlined in the text. Circles for OBS1, triangles for OBS2, gray symbols for Dd-to-Aa adaptation and purple symbols for Da-to-Ad adaptation. Rendered line is a slope of 1.0 with zero offset (perfect prediction of observed data). From left to right the unique hue settings are found at  $\sim 20^\circ$  for red,  $\sim 150^\circ$ - $200^\circ$  for yellow,  $\sim 230^\circ$  for green, and  $\sim 320^\circ$ - $350^\circ$  for blue.*

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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, see the bottom panel of Fig. 2), it is a very reasonable question to explore. An experiment was completed using the protocol and experimental setup described in the *Materials and Methods* section. The same two observers completed these observations. 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<sup>2</sup> 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. 10 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. Interestingly, results that included the same two observers from thirty years earlier suggested that the R background was indeed neutral as they were used to derive the vk20 model. Can both be true? The newer experiments were completed at a higher luminance level, so that could be one factor. More importantly, however is that both observers aged over thirty years between the two experiments, from their mid-twenties to their mid-fifties. Their ocular lens transmittance certainly decreased in the short wavelengths of the visible spectrum (lens yellowing) over that time. That means that the stimuli reaching the retina for the R adaptation condition are significantly more yellow than thirty years previously. While the R background could look neutral in both cases due to long-term adaptation to the yellowing of the lens, it is not surprising that a stimulus that was found to be the reference point for adaptation 30 years ago is slightly too yellow now. This explanation, based on aging/yellowing of the lens, also can explain the changes in the three D parameters in Table 4 from the original

experiments and the current experiments that show a decrease in the degree of adaptation to both illuminants A and D65. In other words, they both look slightly yellower than they did 30 years ago. Thankfully that is not generally noticed in day-to-day color judgements. 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.

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*Figure 10. 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).*

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## **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. No significant differences were found for OBS2 with only eight replications and the small effect sizes measured for OBS1 are only statistically significant due to the large number of repeated measurements (60). 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, the previously published vk20 chromatic adaptation model was further explored with the new data and it was illustrated that the proposed reference adaptation condition of 15000K is psychophysical plausible and might also depend significantly on observer age and individual differences.

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### **Author Contributions**

The author completed all roles in the CRediT taxonomy for this paper.

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Figure 1.

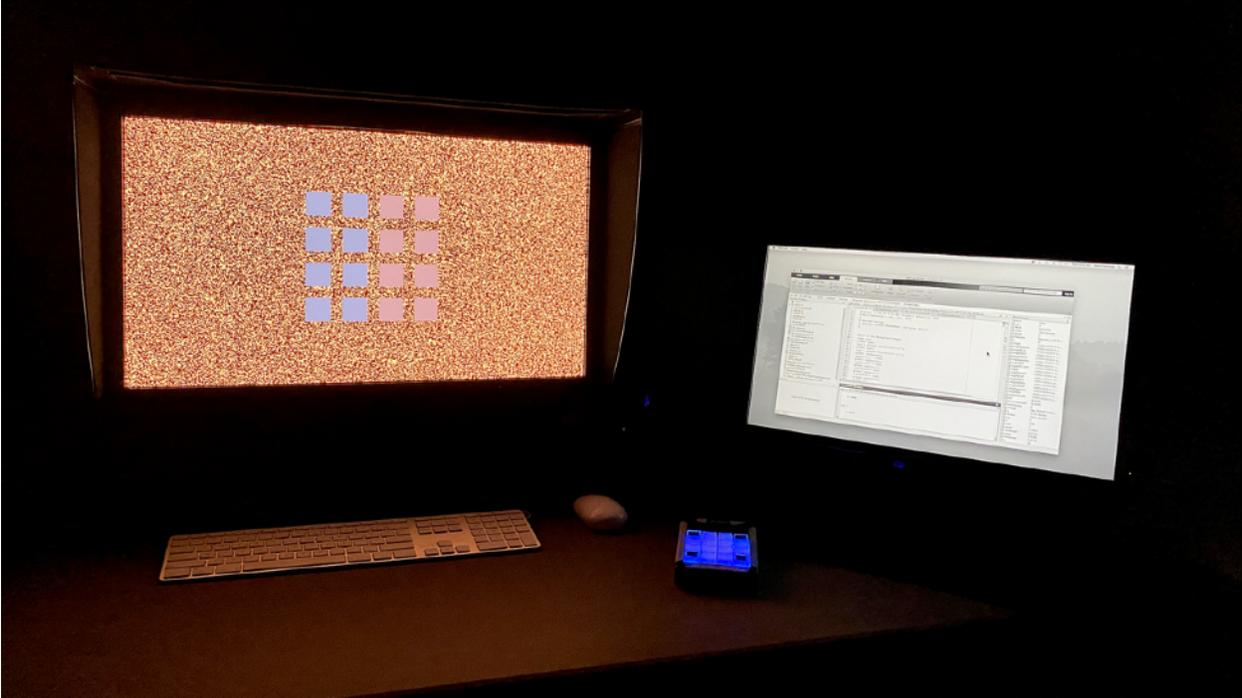


Figure 2.

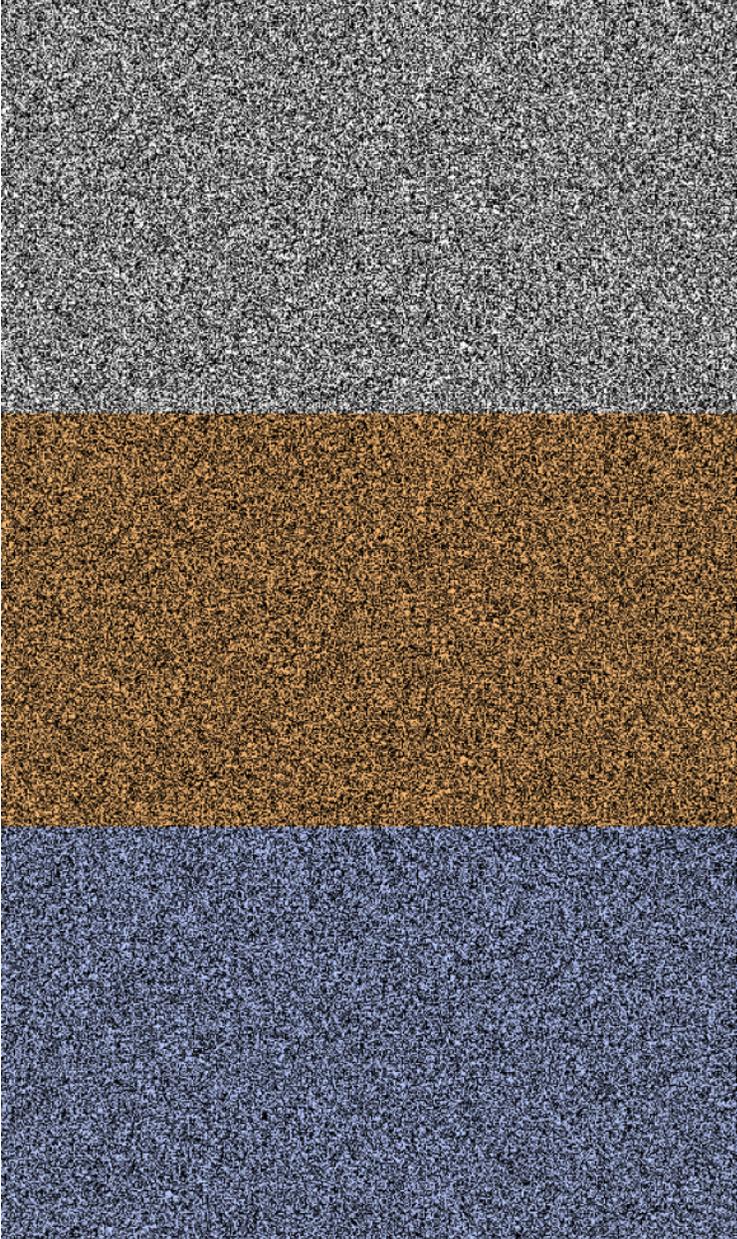


Figure 3.

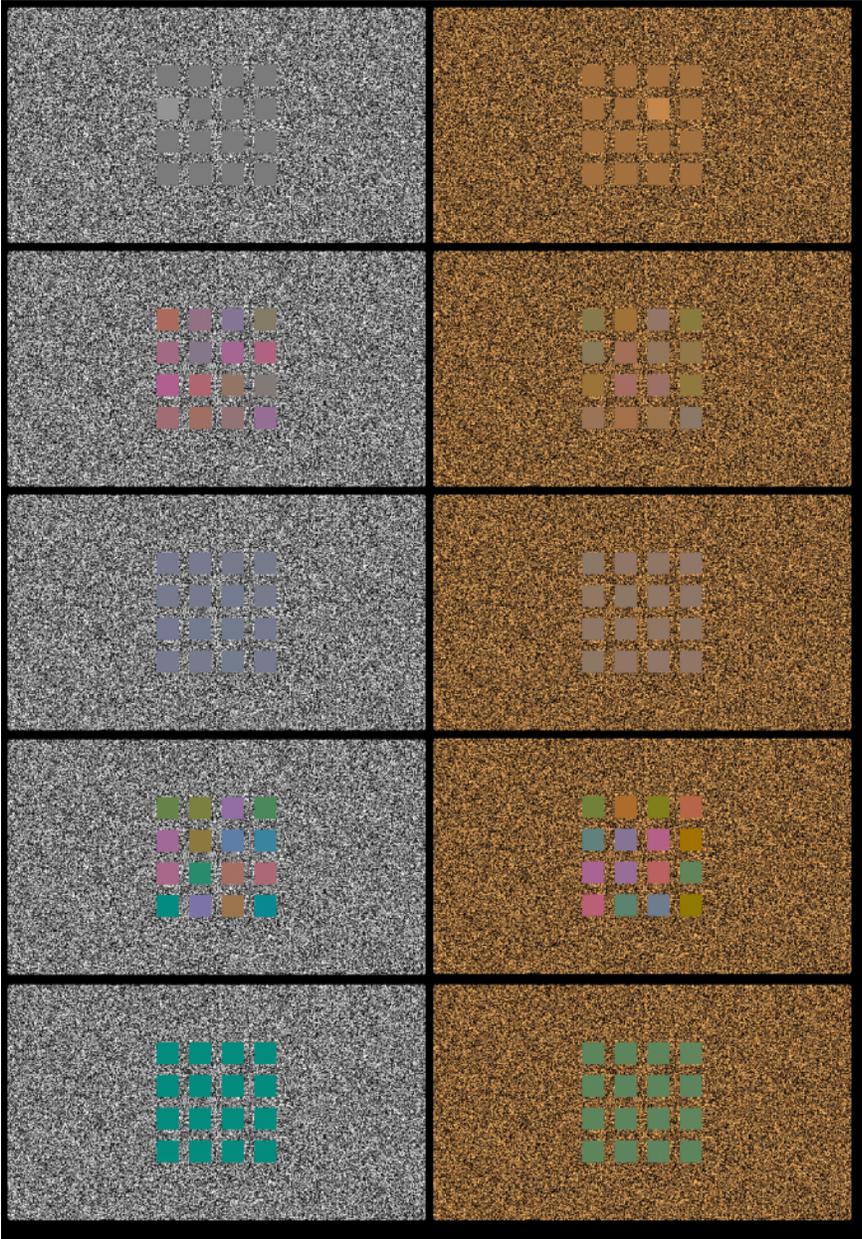


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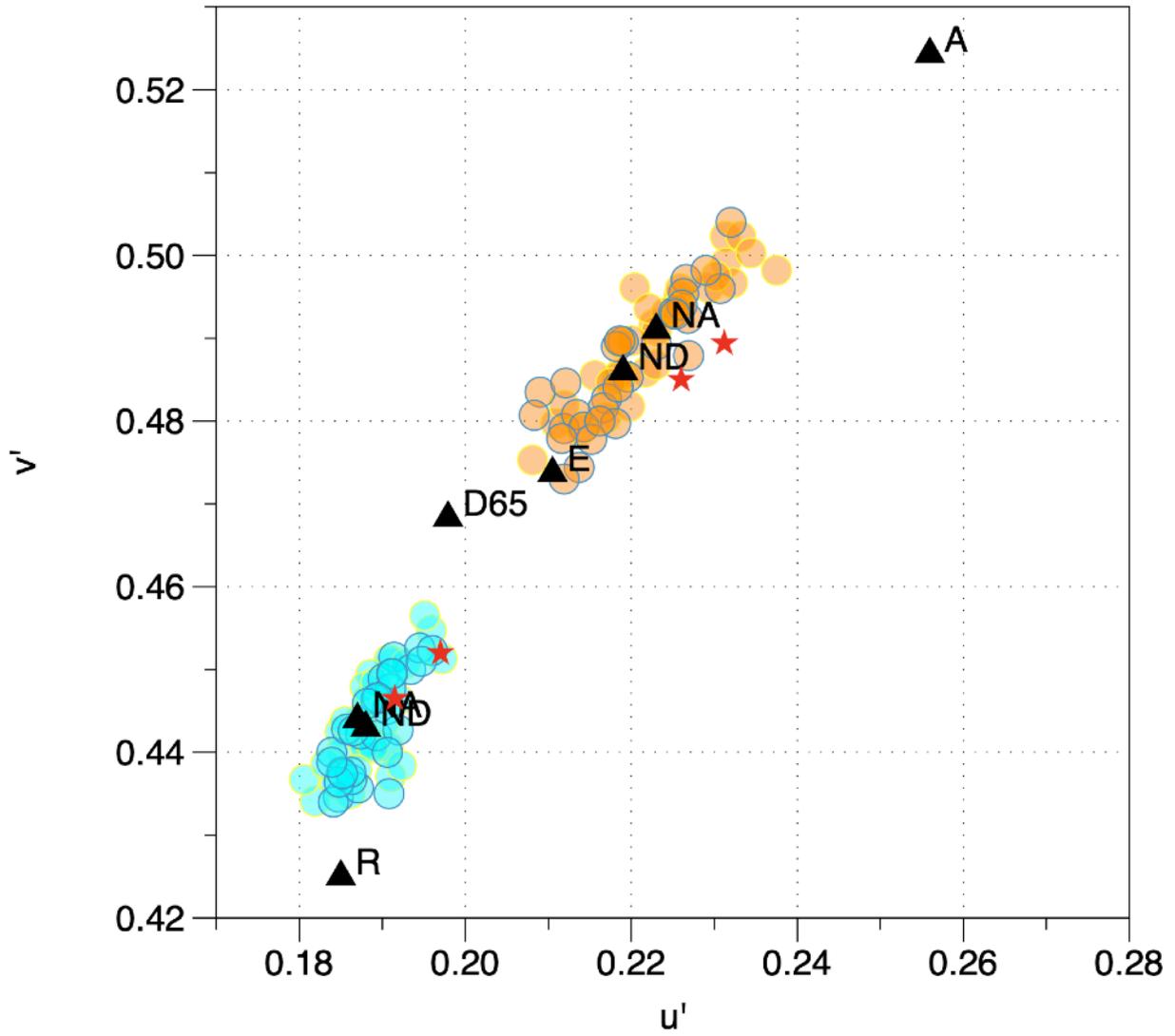


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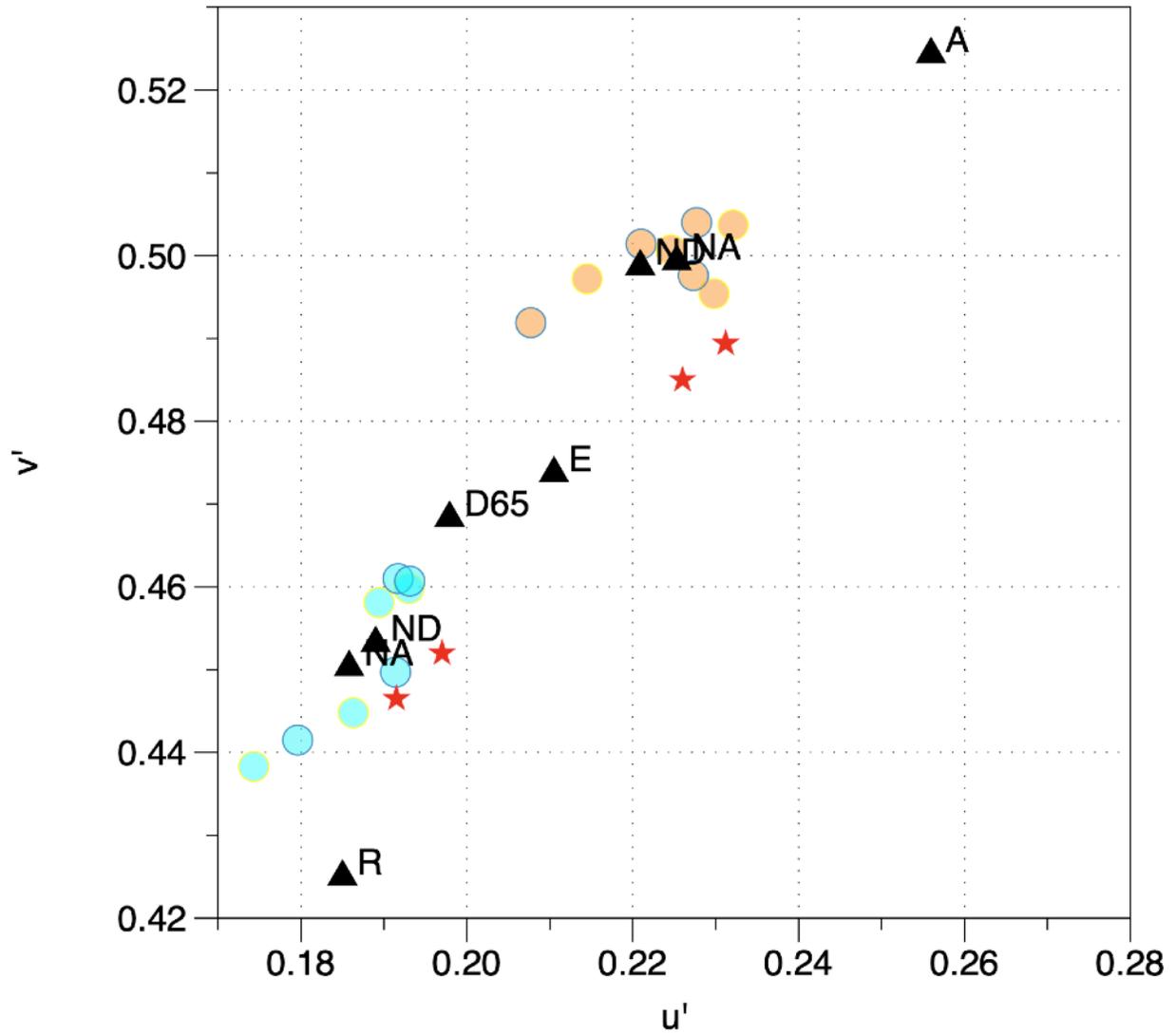


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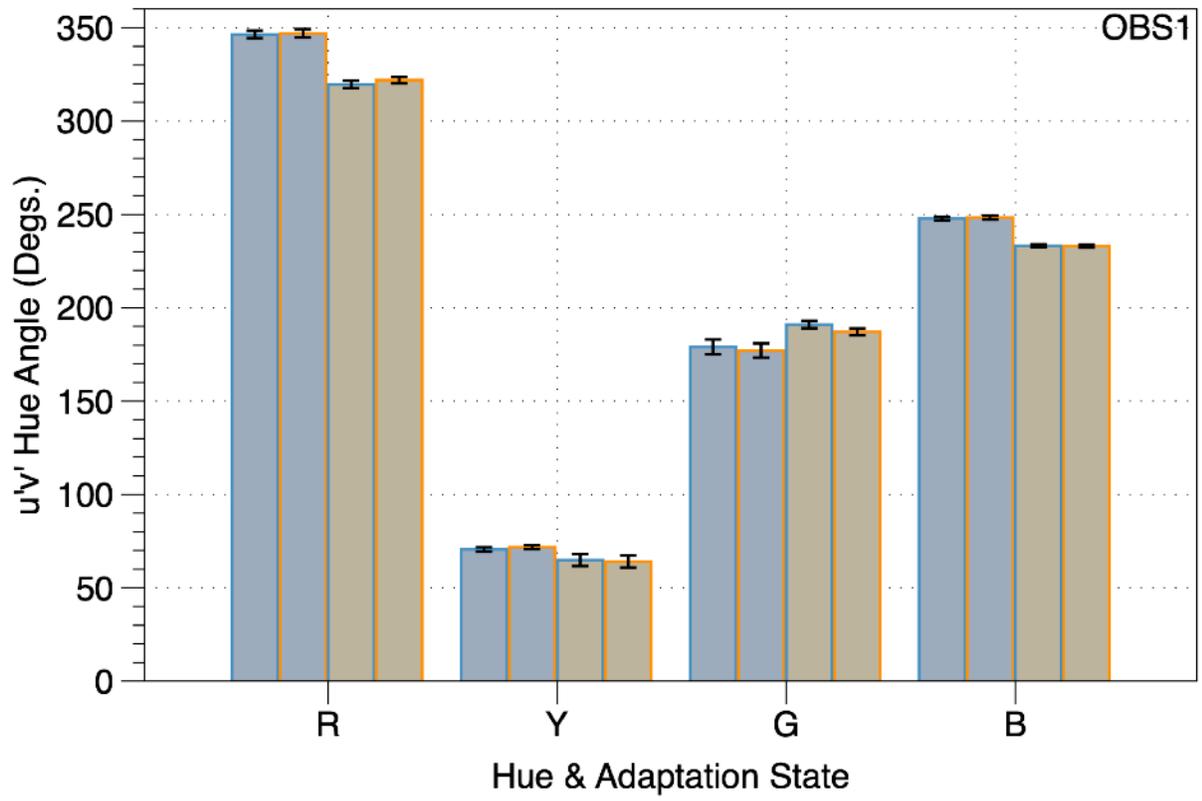


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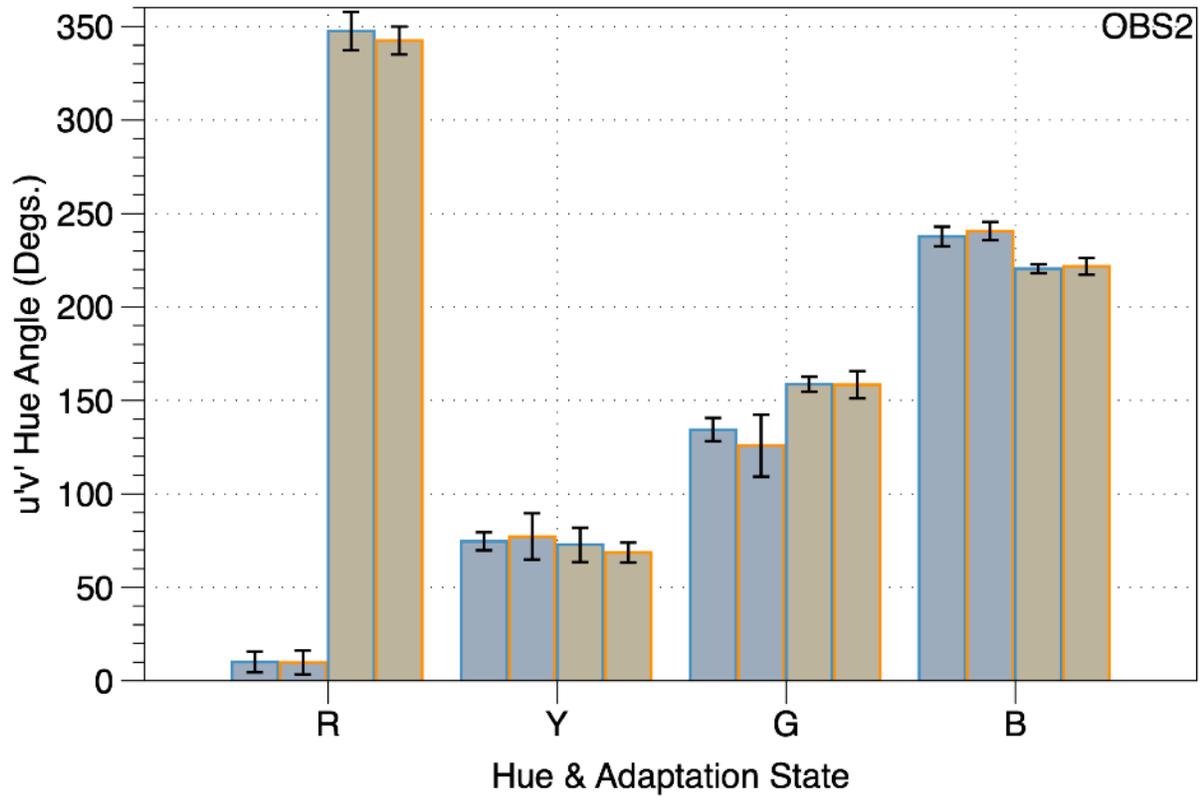


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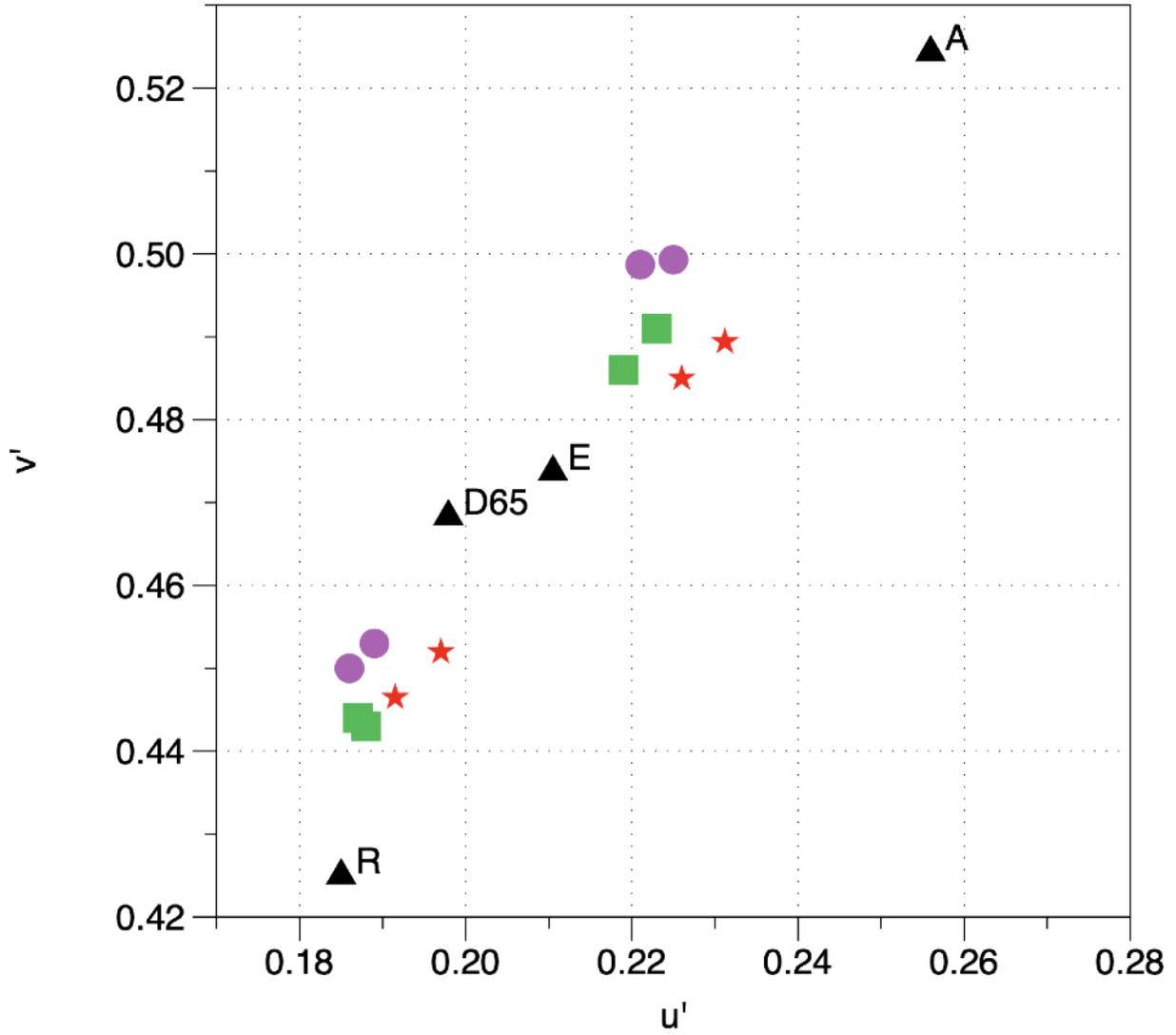


Figure 9.

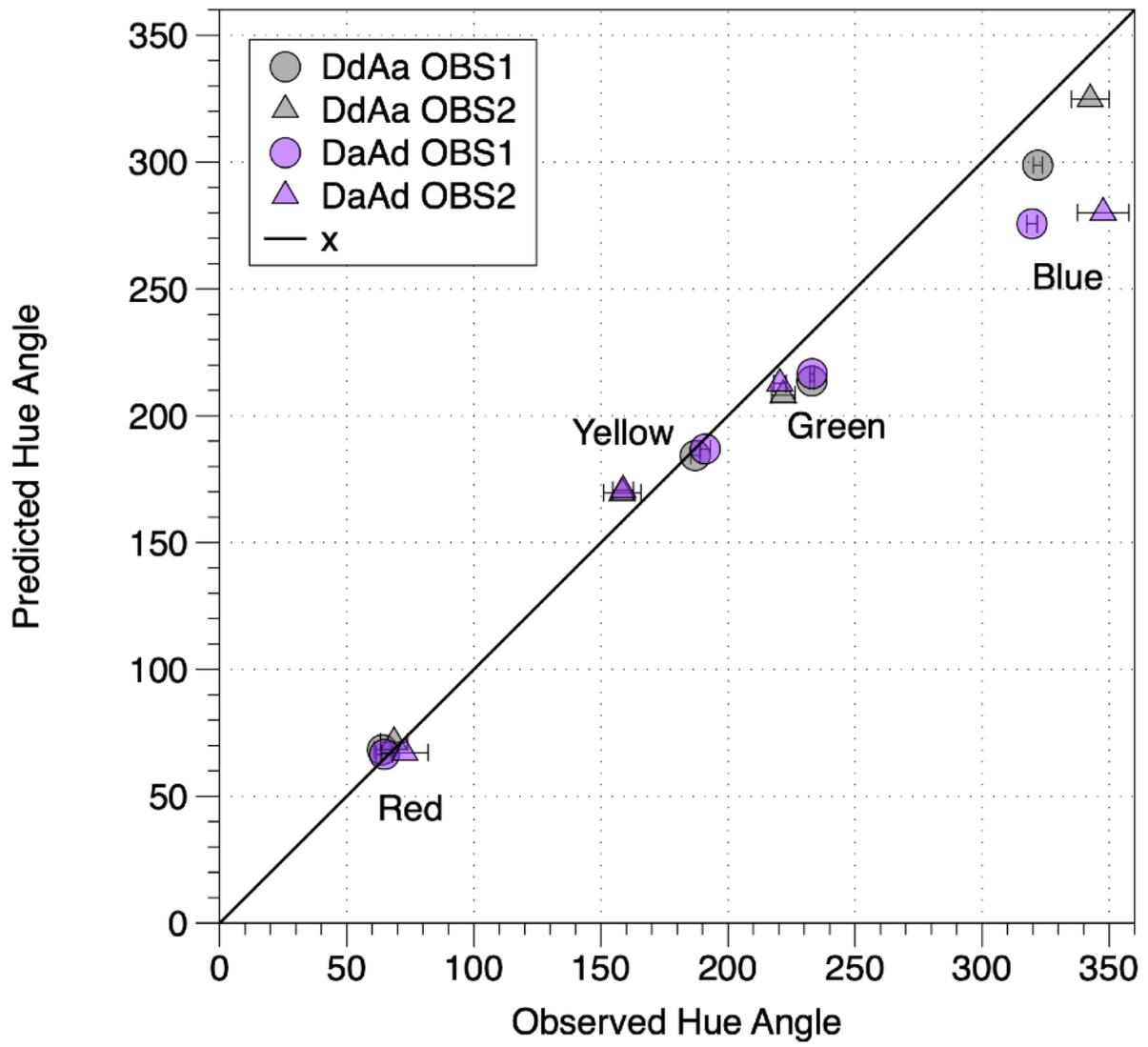


Figure 10.

