

Von Kries 2020: Evolution of degree of chromatic adaptation

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Abstract

Recent data has shown that the process of chromatic adaptation might be asymmetrical, or irreversible, and that this effect might be more than simply a manifestation of the time course of adaptation. This paper introduces a simple modification of the von Kries chromatic adaptation transform, referred to as vK20, that can account for the asymmetry in chromatic adaptation through inclusion of previous adapting conditions. Also introduced is a new reference chromaticity (~15000K) for degree of adaptation that seems more physiologically plausible than the commonly used equal-energy (EE) illuminant or CIE illuminant D65.

Introduction

In 1902, von Kries published his hypothesis on chromatic adaptation as a conceptual extension Grassmann's laws of additive color mixture to span changes in appearance across differences in illumination color.[1] Modern interpretation of the von Kries hypothesis has resulted in the well-established and widely-recognized von Kries chromatic adaptation transform as summarized in Eq. 1 where LMS are the initial cone responses, $L_nM_nS_n$ are the cone responses to the adapting stimulus (often taken to be a similarly-illuminated diffuse white) and $L_aM_aS_a$ are the post-adaptation cone signals.[2] The von Kries hypothesis suggests that adaptation in the three cone types is independent and inversely proportional with the response to a neutral adapting stimulus.

$$\begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} = \begin{bmatrix} \frac{1}{L_n} & 0 & 0 \\ 0 & \frac{1}{M_n} & 0 \\ 0 & 0 & \frac{1}{S_n} \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (1)$$

Various modifications and adjustments to the basic von Kries model have been proposed and evaluated over the last century. Despite that inevitable progress of scientific research, the most accurate general-purpose chromatic adaptation transform, incorporated in CIECAM02 and the CAM16 variant, is a simple von Kries model with slight modifications of the spectral definitions of the LMS (sometimes called RGB) fundamentals.[2]

Recent work on extremely precise measurement of corresponding colors data has illustrated two important points. [3-5] The first is that there are significant individual differences in the mechanisms of adaptation (on top of the differences in spectral sensitivities referred to as observer metamerism). The second point is that chromatic adaptation was observed to not be reversible as illustrated in Fig.1

Figure 1 illustrates an asymmetric matching situation used to measure corresponding colors. An initial test color α 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 α . (Note that this match will be neither a tristimulus

match, nor a material match to color α 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 β . If color α has identical tristimulus values (*i.e.* cone fundamentals) with color β , then chromatic adaptation is reversible. If color α is not identical to color β then chromatic adaptation is not reversible. Possible causes of a lack in reversibility could be experimental biases or physiological mechanisms with hysteresis.

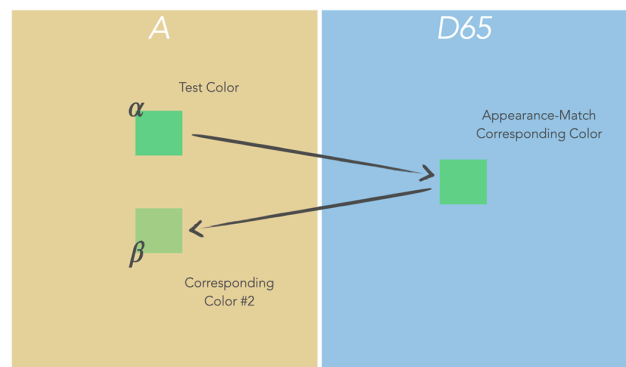


Figure 1. Conceptual illustration of the lack of reversibility in chromatic adaptation. If color α is not identical with color β , then chromatic adaptation is not reversible.

Cai *et al.*[4] made very precise measurements of corresponding colors in a paradigm similar to that illustrated in Fig. 1 and showed clear and significant lack of reversibility in chromatic adaptation (*i.e.* color α was never identical with color β). 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 and underway to unequivocally establish the lack of reversibility in chromatic adaptation.

Fairchild[5] 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.*) The proposed concept of a bidirectional chromatic adaptation transform is fully formulated and specified in this paper.

A Bidirectional CAT: vK20

Current instantiations of the von Kries chromatic adaptation transform typically include a degree of adaptation factor, D . The D factor specifies the perceived neutral point for a given adaptation condition and is normally computed as a proportion of the distance from a reference chromaticity that is putatively defined to always appear neutral when it sets the state of adaptation and the prevailing adapting chromaticity. In CIECAM02/CAM16, the reference chromaticity is EE. Thus the predicted neutral point always falls on a straight line in chromaticity space between EE and the adopted adapting chromaticity. The D factor in CIECAM02/CAM16 is defined as an increasing function of adapting luminance. In some earlier models, D was also a function of adapting chromaticity.[2]

Various data sets described in this paper illustrate that the longstanding assumption that neutral lies on a straight between EE (or D65) and the adapting chromaticity is not strictly valid. Data illustrating that chromatic adaptation is not reversible also suggest a more robust model for computing D is required. These observations have led to the asymmetric, bidirectional model of chromatic adaptation suggested by Fairchild[5] and fully described herein, vK20.

The vK20 model simply relies on three chromaticities, and three D factors, to accurately describe perceived neutral in any adapting situation and intrinsically predict observed departures from reversibility. The structure of vK20 is given in Eq. 2. As in the typical von Kries transformation, LMS refer to the initial cone responses and $L_aM_aS_a$ refer to the post-adaptation cone signals. $L_nM_nS_n$ also still refer to the cone responses for the adapting illuminant, however, in vK20, $L_rM_rS_r$ refer to the responses for the reference illuminant (taken to be $u' = 0.185$, $v' = 0.425$, approximately 15000K, sky blue) and $L_pM_pS_p$ 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.

$$\begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} = \begin{bmatrix} \frac{1}{(D_n L_n + D_r L_r + D_p L_p)} & 0 & 0 \\ 0 & \frac{1}{(D_n M_n + D_r M_r + D_p M_p)} & 0 \\ 0 & 0 & \frac{1}{(D_n S_n + D_r S_r + D_p S_p)} \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (2)$$

The strict definition of time for the specification of "preceding/previous" and the "current" adaptation is not set in this paper. However all of the data presented in this paper are for experiments in which the "current" state of adaptation would traditionally be considered "steady state" and are measured after adaptation periods ranging from two to five minutes. "Immediately preceding" refers to the steady-state adaptation just prior to the onset of the "current" adapting background. For the data in this paper, that is 2-5 minutes preceding. Strict definitions of temporal adaptation functions would be insightful to extend the current model to a continuous time domain.

This model is capable of predicting the observed lack of reversibility of chromatic adaptation by having adaptation depend on three chromaticities rather than the normal one with the simple von Kries model or two in models that include incomplete chromatic adaptation (such as CIECAM02). To summarize, vK20 degree of adaptation depends on the current, previous, and reference (~15000K) adaptation states, CIECAM02/CAM16 degree of adaptation depends on the

current and reference (EE) adaptation states, and the traditional von Kries model depends only on the current adaptation state.

In the traditional von Kries model, perceived neutral is defined as a point $L_nM_nS_n$. In CIECAM02/CAM16-like models, perceived neutral falls on a line between $L_nM_nS_n$ and $L_rM_rS_r$ (EE). In vK20, perceived neutral falls in the chromaticity gamut area enclosed by $L_nM_nS_n$, $L_rM_rS_r$ (~15000K), and $L_pM_pS_p$. In fact the vK20 perceived neutral point can be modeled as any chromaticity if negative values of the $D_nD_rD_p$ factors are allowed (they must always sum to 1.0 however).

The following sections examine some predictions of the vK20 model.

Reference Point: A Re-Examination of Fairchild (1990) Incomplete Chromatic Adaptation

Some early measurements of incomplete chromatic adaptation include the work of Breneman,[6] that was the inspiration for Fairchild's research[7] leading to the formulations of degree of adaptation equations such as those found in CIECAM02 and CAM16. The main result of from the Fairchild 1990 work is illustrated in Fig. 2.

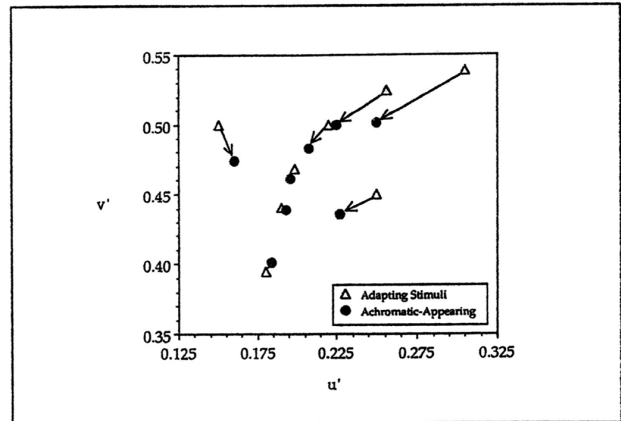


Figure 4-2. Results of experiment 5 for the average of 3 observers. Filled symbols represent achromatic-appearing stimuli under adaptation to various adapting chromaticities represented by the filled symbols. Standard errors of the mean estimates are approximately the size of the plotting symbols.

Figure 2. Incomplete chromatic adaptation results from Fairchild 1990.[7] Filled symbols represent adapting chromaticities and filled symbols represent corresponding achromatic-appearing chromaticities. Reproduced with permission.

Figure 2 illustrates apparent neutral (filled symbols) for eight different adapting chromaticities presented on a CRT display. The adapting chromaticities along the Planckian/daylight loci were infinite K, D93, D65, D50, A, and 2000K. In addition pink and green adapting chromaticities were evaluated.

These results were used to support the idea that average daylight was some form of anchor point for chromatic adaptation that represented a chromaticity that always appeared neutral. This supported much earlier conclusions on the perception of white by Hurvich and Jameson.[8]

Models of degree of adaptation were initially proposed to be complex functions of adapting chromaticity and luminance with D65 reference points[9,10] and later simplified to be dependent on only luminance and to use the EE reference point as in CIECAM02.[2]

Recent experimental results, discussed below, suggest that perhaps the assumption of D65 or EE normalization points

might make chromatic adaptation modeling more complicated than necessary. As a minimum, D65 is unquestionably more neutral under a wider variety of adaptation conditions than EE [11-13]. This prompted a re-examination of the original results from Fairchild. As can be seen in Fig. 2, especially for the pink and green adaptation chromaticities, the line segment connecting the adapting stimulus to the neutral-appearing stimulus does not project toward D65 or EE. Instead, a new reference point was derived that would allow all the results to be predicted with a constant degree of adaptation, thus eliminating any need for a function of chromaticity. This derivation is illustrated with the vectors in Fig. 3 superimposed on the original results. The vectors converge on a new proposed reference chromaticity that is approximately represented by a Planckian radiator at 15000K, which in nature represents blue skylight.

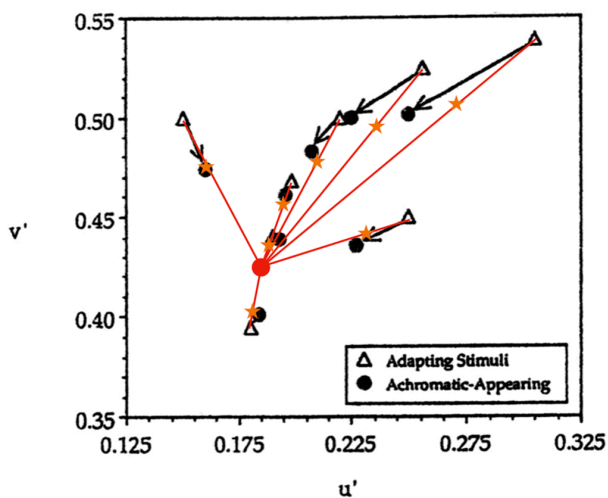


Figure 3. Results of Fairchild (1990) [7] with superimposed predictions of 70% complete adaptation for all adapting chromaticities relative to a reference chromaticity of ~15000K (blue sky). Red circle is the ~15000K reference point, orange lines represent projections to that point from each adapting chromaticity, and orange pentagrams represent the prediction of 70% adaptation from that reference to the adapting chromaticities.

The predictive quality of the vK20 model for these data is outstanding. While D parameters could be fit to make perfect predictions of all the data, a physiologically-plausible model should have consistent D values for all these adaptation states since they were at a constant luminance (100nits for white). The predictions illustrated in Fig. 3 all use $D_n = 0.7$, $D_r = 0.3$ and $D_p = 0.0$ with a reference chromaticity of ~15000K ($u' = 0.185$, $v' = 0.425$). $D_p = 0.0$ is considered theoretically appropriate since the previous adaptation state was randomized in those experiments and not systematically varied or controlled.

When the predictions in Fig. 3 are made with an EE reference point (as in CIECAM02/CAM16), accurate predictions are not possible for the D65, A, pink, and green adapting chromaticities. The optimal D_n values with an EE reference range from 0.4 to 1.4 with a mean of 0.74 and standard deviation of 0.37 (50% of the mean value). Instead, when using the newly derived reference point of ~15000K, six of the eight adaptation states are predicted within the standard error of the mean estimates and the other two are roughly within inter-observer variability. The optimal D_n values in the

vK20 formulation range from 0.6 to 0.8 with a mean of 0.71 and standard deviation of 0.09 (less than 13% of the mean value). Recall that the predictions shown in Fig. 3 are using a D_n of 0.7 for all adaptation states, and not the optimized individual values. Simply put, this viewing condition results in 70% complete adaptation relative to ~15000K, which is a much more physiologically plausible, and consistent, than previous empirical models.

Hands: Hiding in Plain Sight

Another related experiment was published by Fairchild in 1992.[14] In it, the displayed adapting stimuli were presented with images of hands holding the adapting image and with no hands (normal soft display) to study degree of adaptation and cognitive discounting with context. The basic idea was that hands in the image would provide more context for the change in white point and thus more complete chromatic adaptation and, indeed, that was the case as illustrated in Fig. 4. Also illustrated in Fig. 4 are predictions of the vK20 model with different D parameters (labelled in the figure) for the Hands vs. No Hands conditions, but identical for each adapting chromaticity and thus theoretically consistent. The in the Hands cases, adaptation was 95% complete, while in the No Hands condition, adaptation was 85% complete. Such a simple explanation of the results as an increase in degree of adaptation is not possible with reference chromaticities of D65 or EE, but falls out naturally with the ~15000K reference point.

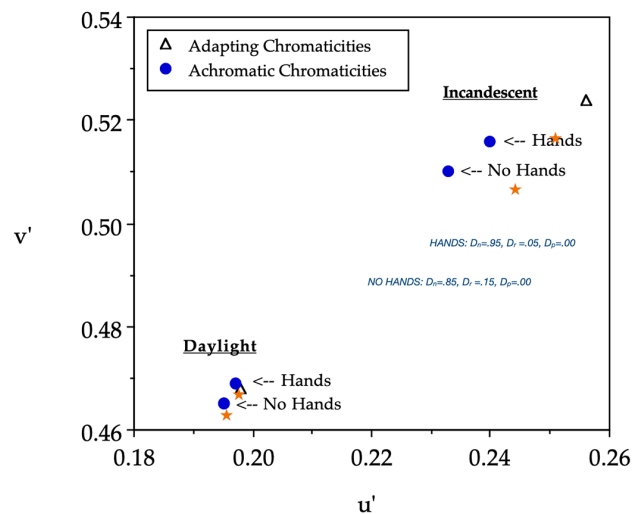


Figure 4. Hands vs. No Hands degree of chromatic adaptation results from Fairchild (1992) along with predictions (orange pentagrams) of the vK20 model described in this paper. Base figure reproduced with permission.

As in Fig. 3, the predicted results for III. A adaptation are shifted to the right on the $u'v'$ diagram. This is suggestive of a nonlinear path for degree of adaptation, perhaps following the Planckian locus, instead of a straight line between the reference and adapting chromaticities. This possibility is not pursued in this paper since newer data do not follow the same trend and since the vK20 model could again predict the results exactly if the D parameters were allowed to vary between D65 and A adaptation, which is less theoretically rewarding.

Additionally the order of adaptation between D65 and A was studied as a controlled variable with one set of observers adapting to D65 first and another to A first with five minutes of

adaptation in each case.[14] The results illustrated that adaptation was more complete to the first condition viewed. This result was noted, but not studied further.[14] In hindsight, it is clear that this result was perhaps an early observation of the lack of reversibility in chromatic adaptation.[4] The vK20 model should be able to address this discrepancy. Fig. 5 illustrates the original reversibility data with the vK20 predictions overlaid.

In this case, consistent sets of $D_n D_r D_p$ reasonably predict the trends in both sets of data. For adaptation to the first-view white point, adaptation is 90% complete with $D_n = 0.9$ and $D_r = 0.1$. When the opposite adaptation white point was evaluated first, it then has an influence on the final state of adaptation through a non-zero D_p value. In those cases $D_n = 0.8$, $D_r = 0.1$, and $D_p = 0.1$. Once again, the vK20 model, with consistent D parameters for both adaptation conditions can explain the results in a consistent manner. The concept that adaptation to the second-viewed adapting stimulus is slightly impacted by the previously-viewed adapting stimulus, even when the adapting duration is long enough to reach steady-state adaptation, is born out by the model predictions as well as more recent experimental data.[4] The triangle sketched in Fig. 5 illustrates the gamut of gray points with non-negative D values between Ills. D65 and A and the ~15000K reference point. Note that any values for gray point can be predicted if the D values are allowed to be negative and optimized to individual results.

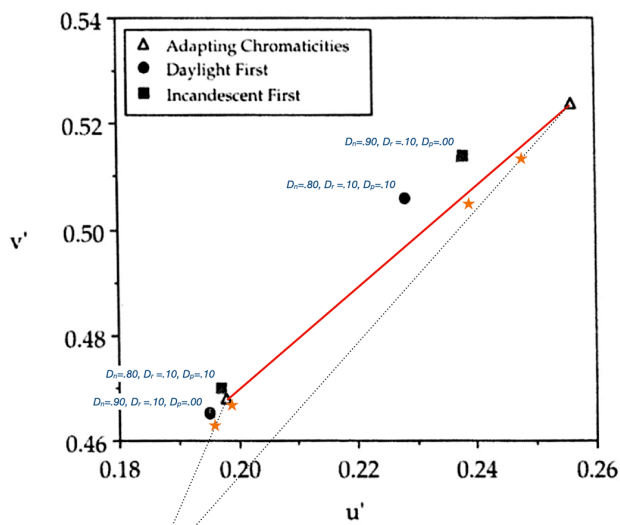


Figure 5. Reversibility of chromatic adaptation results from Fairchild (1992) overlaid with prediction of the bidirectional vK20 model (orange pentagrams) as described in the text. Base figure reproduced with permission.

Preliminary Results: Reversibility Study

A new study is underway to very precisely and accurately test the reversibility of sensory chromatic adaptation to illuminants D65 and A. The paradigm and results are similar in nature to the results of Fairchild.[7,14] However the data are being collected on a modern display with larger spatial extent, wider color gamut, and a higher luminance (400 nits). In this experiment the observer adapted to D65 first then A (neutral points labelled ND) on half the trials, while adapting to A first and then D65 in the other half of the trials (neutral points labelled NA). While the final data set is not yet available, one typical set of results for one observer are illustrated in Fig. 6

Two strong conclusions can be made from these preliminary data. First, adaptation to D65 is not complete and is indeed shifted toward ~15000K, the same assumptions for the reference point that predict the Fairchild 1990 data predict these results. Note that the reference point was determined solely from the Fairchild 1990 data and not fitted in any way to these results. D65 or EE reference points cannot be used to adequately predict these data. Second, there is a hysteresis effect, or lack of reversibility and the first-viewed adaptation stimulus impacts adaptation to the second-viewed adaptation stimulus (despite over 5 minutes of adaptation, normally accepted to be well more than the time required to reach steady state [2]). The results are well-predicted using common vK20 D values for all data points and using the ~15000K reference point as illustrated with the adaptation point gamut triangle and predicted points. For cases where adaptation was first to the opposite white point, values of $D_n = 0.6$, $D_r = 0.3$, and $D_p = 0.1$ explain the results. For the cases where the same adaptation state was viewed first in the experiment, values of $D_n = 0.7$, $D_r = 0.3$, and $D_p = 0.0$ explain the results. In other words, the previous adaptation state has a 10% effect on the degree of adaptation when present and a 0% effect when absent. Again, the predictions are consistent with the theory.

These predictions are well within the uncertainty of a single memory matching trial. Further analysis will be completed when the full study results (30 replicates of each adapting condition and more corresponding colors than just gray) are published to refine the vK20 model and the related understanding of adaptation reversibility.

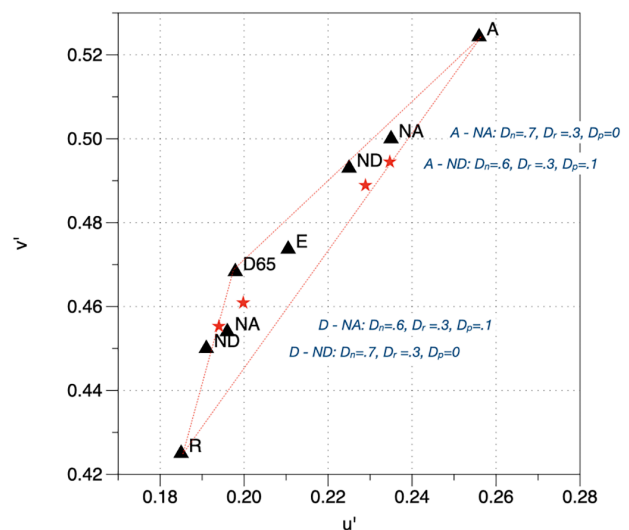


Figure 6. New preliminary data on the reversibility of chromatic adaptation between illuminants D65 and A along with predictions of the bidirectional vK20 model with constant theoretical parameters for each condition (red pentagrams). Note that, as a mathematical definition, optimized parameters can fit the results perfectly. Thus no such optimization was completed.

Other Data

The vK20 chromatic adaptation model is supported by, or at least has been elucidated by, additional recent and historical experiments. Several of these examples are discussed below.

Ma *et al.*[11] recently examined 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. Smet *et al.* [12,13] also examined the most unique white under various viewing conditions to relate that result to the chromatic adaptation transforms. In the Ma *et al.* work, adaptation apparently depended on the adapting surround, the stimulus itself (as has been observed in previous experiments where the stimulus was continuously adjusted[7]), and the reference adaptation point. While the authors suggested a reference point close to D65, as in the earlier work,[12,13] might be appropriate, they modeled degree of adaptation relative to EE as is done in CIECAM02/CAM16. Those results clearly illustrate that the EE based degree of adaptation computation is not accurate. 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 $D_p = 0.33$. Further exploration of these data with a vK20-type model is warranted.

Hunt & Winter[15] 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[8] 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 by vK20 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[15] also showed a similar luminance dependence although they tested only two luminance levels.

A related phenomenon was observed by Winkler *et al.*[16] who illustrated a blue-yellow asymmetry in perceived saturation for a given cone contrast. Their observation was that bluish stimuli appear less saturated than yellowish stimuli and that the blue tint in an image is more likely to be attributed to illumination while a yellow tint is more likely to be attributed to material objects. This observation is consistent with chromatic adaptation having a principal axis along the Planckian locus where most natural illumination falls and an ability to much more completely adapt to bluish illumination than yellowish. This is very consistent with the data on incomplete chromatic adaptation presented in this paper and with the concept of a chromatic adaptation reference point of sky blue (~15000K).

Lastly, 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.[17,18] 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 fills the bill. (Note: A separate pilot experiment for adaptation to 15000K was run after this paper was initially submitted and that chromaticity can indeed appear achromatic.)

Conclusions

In MacAdam's translation of von Kries 1902, after explaining his hypothesis of chromatic adaptation, suggest that "if some day it becomes possible to distinguish in an objective way the various effects of light by direct observation of the retina, people will perhaps recall with pitying smiles the efforts of previous decades which undertook to seek an understanding of the same phenomena by such lengthy detours." [1] Amazingly, CIECAM02 and CAT16 returned to von Kries after many excursions over the 20th century. The herein proposed little polishing, vK20, makes the von Kries hypothesis more robust and theoretically well grounded. However, there is still need to figure out exactly how to predict the three D components from the viewed scene and history alone. There is no doubt that they will vary for different scene configurations, luminance levels, modes of viewing, experimental tasks, *etc.*

In summary, Table 1 provides the approximate D factors used to describe the vK20 model predictions of the various data sets discussed in this paper and illustrating its compatibility with existing standard models. Based on these initial analyses, it is expected that the vK20 model will predict corresponding colors data with at least 50% less systematic error than current state-of-the-art chromatic adaptation models such as CAT02 and CAT16. Much of this improvement is due to the more appropriate reference chromaticity and the remainder due to accounting for preceding state of adaptation. It appears that both features are worthy of consideration in any forthcoming CIE models.

Table 1. vK20 degree of adaptation coefficients for the various experiments and models described in the text. All use the ~15000K reference point unless indicated.

CONDITION	D_n	D_r	D_p
Fairchild [7]	0.7	0.3	0.0
Hands [14]	0.95	0.05	0.0
No Hands [14]	0.85	0.15	0.0
Ordinal 1 st [14]	0.9	0.1	0.0
Ordinal 2 nd [14]	0.8	0.1	0.1
Reversibility Trial 1 st	0.7	0.3	0.0
Reversibility Trial 2 nd	0.6	0.3	0.1
Ma <i>et al.</i> [11]	~0.33	~0.33	~0.33
Hunt & Winter [15]	~0.6	~0.2	~0.2
Hurvich & Jameson [8]	0.70	0.30	0.0
Simple von Kries	1.0	0.0	0.0
CIECAM02 / CAM16	D Computed	$(1-D)$ Ref. = EE	0.0

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