Role of color memory in successive color constancy

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We investigate color constancy for real 2D paper samples using a successive matching paradigm in which the observer memorizes a reference surface color under neutral illumination and after a temporal interval selects a matching test surface under the same or different illumination. We find significant effects of the illumination, reference surface, and their interaction on the matching error. We characterize the matching error in the absence of illumination change as the "pure color memory shift" and introduce a new index for successive color constancy that compares this shift against the matching error under changing illumination. The index also incorporates the vector direction of the matching errors in chromaticity space, unlike the traditional constancy index. With this index, we find that color constancy is nearly perfect. © 2008 Optical Society of America

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1. INTRODUCTION

Color constancy is the phenomenon by which perceived object color tends to stay constant under changes in illumination. On a temporal scale, color constancy may be separated into two components: simultaneous and successive. Simultaneous color constancy occurs when an observer views a scene simultaneously lit by two or more different light sources and perceives identical surface materials to have the same color, despite being differentially illuminated – for example, where part of a single surface is directly lit and the other part in shadow, lit only via the ambient illumination, yet the observer perceives the surface as a single constant object of the same color throughout. This discounting of the spatial change in illumination and recovery of constant surface reflectance across the shadow border is a form of color constancy.

Successive color constancy instead involves discounting temporal changes in illumination. Here the observer views an object first under one illumination, and after a certain time lapse, views the same object under a different illumination and perceives the object's color to be the same although it reflects different light spectra in the two instances. Here color constancy clearly requires at least two distinct processes: color memory, in which the object's color under the first illumination must be recorded in memory (at some level); and a color transformation, in which the two different light spectra under the two different illuminations are compared and perceived to correspond to the same object. The observer must compare the object he views now with what he has previously viewed. Therefore, in successive color constancy, the effect of color memory must be considered.

Many experimental measurements of color constancy focus on simultaneous color constancy. These typically employ asymmetric color matching paradigms, in which observers view two arrays of colors under two different illuminations side by side and make matches between them [1–6]. Successive color constancy, which occurs often in natural visual tasks, has received variable attention in the laboratory. Experimental approaches include measuring observers' ability to discriminate between rapid temporal changes in illumination versus material in a multicolored array [7] and achromatic adjustment tasks in temporally changing contexts or illuminations [8]. The latter task requires color memory for "white," at some level, and the former requires short-term memory of overall color distributions. Although some achromatic adjustment experiments do take memory effects into account, for example, via the concept of an "equivalent illumination" and its effect on "white" [8], few studies [9] explicitly take color memory of individual, identifiable surfaces into account in evaluating color constancy. Here we are particularly interested in the relationship between color constancy and color memory, and to this end, we investigate successive color constancy for real 2D color patches. We introduce a new color constancy index that incorporates color memory.

2. BACKGROUND

A. Color Memory

The study of color memory is generally approached on two different levels: sensory and cognitive [10,11]. Here, we will address the sensory approach only. Sensory-based memory experiments typically employ isolated color patches or monochromatic lights as stimuli to avoid any cognitive effects that may influence perception. Most such studies report a shift in color memory away from the originally presented stimulus. The memory shift varies according to the time course, stimulus type, and matching technique, as well as the individual's ability to memorize color, but the conclusion is the same from all studies: color memory is not perfect [12–18].

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The most consistent shift in color memory occurs along the saturation dimension. The remembered color is often more saturated than the original stimulus, regardless of the time lapse [12,15–17]. Shifts in the lightness dimension are also well documented. Typically, bright colors tend to be remembered as even brighter and dark colors tend to be remembered as even darker than the originally presented color [15,17].

The question as to how color memory depends on hue has also been examined extensively, but the answer is far less clear. Although most studies report a shift in hue memory, the direction of shift is not systematic [12,15–17]. One hypothesis is that the remembered hue shifts toward the universal "focal color" [19], defined by Berlin and Kay [20] as the best example within each basic color category. Berlin and Kay [20] also suggested that "focal colors" are universally the most accurately remembered within color space, a hypothesis which has received conflicting support [21–23]. Recent studies have also shown that, at the cognitive level, color memory is affected by color categories, which in turn are influenced by linguistic color naming [24–26]. Nevertheless, at the sensory level, it is not possible yet to describe systematically how and why hue shifts occur.

B. Color Constancy and Color Memory

Although several studies have employed a successive color constancy paradigm [15,27,28] and compared successive with simultaneous color matching [15], few have explicitly compared color memory matching and color constancy matching under the same experimental conditions or directly analyzed the relationship between color memory and color constancy. Two notable exceptions are described in more detail below.

Jin and Shevell [9] employed a typical successive color constancy paradigm to investigate color constancy and color memory: they displayed a training color under one illumination (either illumination A or C), then tested the observer's color memory under both illuminations A and C, either 10 seconds or 10 minutes after the training. The training color was presented against a uniform gray background only, or surrounded by eight other uniform color patches (the "complex scene" condition). Only in the "complex scene" condition were the observers' matches consistent with color memory for the spectral reflectance of the surface rather than the receptoral excitations elicited in the training phase. While the reported results demonstrate that color constancy occurs in color memory (on average and under certain conditions), they do not provide information about the relative accuracy of color memory (as a representation of surface properties) under changing illumination, as compared with constant illumination.

Uchikawa *et al.* [29] employed a similar paradigm and investigated the relationship between color memory and color constancy more directly. In their report, memory shifts under constant and changing illumination are plotted together in the CIE u′v′ chromaticity diagram, for two observers. Visual inspection of the diagram suggests no significant difference between memory matching and constancy matching, although the relationship is not explored quantitatively.

C. Color Constancy Index

Most experimental color constancy studies employ the Brunswik ratio (BR), or its close relative, to quantify the extent of color constancy. The BR is typically computed as

$$\mathrm{BR} = 1 - (\text{perceptual shift}/\text{physical shift}). \tag{1}$$

Here, physical shift refers to the change in the reference surface's chromaticity under changing illumination, i.e., the distance between the surface chromaticity under the reference and test illuminations in the u′v′ chromaticity diagram ($\|\vec{S}_p\|$ in Figs. 5 and 6 below). Perceptual shift refers to the distance between the chromaticities of the matched surface and the reference patch under the test illumination ($\|\vec{S}_c\|$ in Figs. 5 and 6) [5]. Perfect color constancy (BR=1) occurs when the perceptual shift is zero, i.e., when the reference and matched surfaces are the same, and therefore have the same chromaticities under the test illumination. A total lack of color constancy (BR =0) occurs when the observer performs a "chromaticity" match instead of a "surface" match, i.e., when the matched surface under the test illumination has the chromaticity of the reference patch under the reference illumination (perceptual shift=physical shift).

The BR has been widely used to measure color constancy, and although in theory it has no lower limit, in practice its range is small but finite; recent studies report values from 0.55 to 0.83, depending on the experimental conditions [2–5,8,28,30]. Nevertheless, most studies that use the BR examine simultaneous color constancy only. For successive color constancy, we suggest that the BR is an unreliable measure, because it does not take into account the effect of color memory [31].

3. METHOD

A. Experimental Setup

The experiment employed the experimental box developed by Ling and Hurlbert [32] in which the observer views real objects illuminated by a hidden data projector. The stimuli were flat uniform color patches printed by a characterized color printer (Epson Stylus Color 980). Surface reflectances of each patch and illumination spectral power distributions were measured by a spectroradiometer (PR-650 Spectrascan) and used to calculate surface chromaticities for all experimental conditions.

Thirteen color patches were selected as reference stimuli. For each of these, we produced one 20 cm × 20 cm "reference plate" with a single 3 cm × 3 cm reference color patch placed centrally on white paperboard and one 20 cm × 20 cm "test plate" with sixteen 3 cm × 3 cm alternative equiluminant color patches arranged in a 4 × 4 grid on white paperboard. The reference patch matched one of the 16 patches in the test plate (i.e., was printed in the same ink). For seven of the thirteen reference stimuli, the chromaticities of the alternative patches varied primarily in saturation only ("saturation series" A–G) and for the remaining six, the alternative test chromaticities varied primarily in hue only ("hue series" A–F). (A second aim of these experiments was to separate the hue and saturation components of color constancy, results for which are reported elsewhere [33].)

The experiment employed five illuminations, all generated by the data projector in the experimental box. These were three standard illuminations corresponding to daylights of 4000, 6500, and 14 5000 K correlated color temperature; one reddish illumination; and one greenish illumination (labeled as D40, D65, D145, Red and Green, respectively). Note that because the illuminations are generated by a data projector, the D40, D65, and D145 lights differ in spectra but are metameric to the standard CIE daylights. Their measured CIE Yxy chromaticity values are shown in Table 1. The chromaticity values were measured as the chromaticity of a perfectly white surface illuminated solely by the test illumination.

Table 2 shows the measured CIE Lu′v′ lightness, hue, and saturation values under D65 illumination for the colors in the saturation series; their hue series counterparts are given in Table 3. We selected the stimuli using three main criteria: (a) the reference colors should cover as large a range of color space as possible; (b) for each reference color, our printer characterization model should yield 16 alternative chromaticities varying only in hue or saturation; and (c) to avoid centroid effects (in which observers select the central choice available in the palette), the reference chromaticities are randomly distributed within the test alternatives (for example, hue series A and saturation series E each has reference chromaticities far from the center of the alternatives' distribution). Some compromises were necessary given imperfections in the printer characterization model. Table 4 provides the closest Munsell color notations for the thirteen reference patches, for illustrative purposes only. Figure 1 illustrates the 16 test alternative chromaticities for saturation series F under the five test illumination conditions, in the CIE u′v′ plane.

B. Experimental Procedure

Figure 2 illustrates the protocol for a typical trial. The observer begins the trial by preadapting for one minute to the D65 reference illumination projected onto the "adaptation plate," a sheet of blank white paperboard. When preadaptation is complete, the experimenter removes the adaptation plate to reveal the reference plate directly beneath. The observer is instructed to memorize the reference color while viewing the reference plate for 10 s. Following the reference viewing phase, the experimenter reinserts the adaptation plate and changes the illumination to the test illumination by pressing a button. The observer then performs an arithmetic task that consists of answering yes or no to a series of written single-digit sums projected onto the adaptation plate (e.g., 3+4+1+9=16, Yes or No?, for which the observer should press the NO button). During the arithmetic task, the experimenter inserts the test plate beneath the adaptation plate, and at the end of one minute, reveals the former by removing the latter. The observer selects the test patch by stating its location on the grid. The next trial then begins with the preadaptation phase. In D65 test illumination sessions, the protocol is the same, but with no preadaptation phase and no change from reference to test illumination.

The entire experiment consisted of five sessions, each corresponding to one test illumination and lasting ≈40 min, except for the D65 sessions, which lasted about 30 min. A single session involved 13 memory trials – one for each reference patch in each saturation and hue series. The sequence in which the reference patches were presented varied between sessions, but was constant across observers. Only one experimenter was required to operate the procedure for one observer, and two experimenters participated overall. The test plates were randomized and rotated within the procedure, so that neither the experimenter nor the observer were able to identify the color patch arrays on the test plate.

Table 1. Measured CIE Yxy Chromaticities for the Five Experimental Illuminations

Illumination	Chromaticity (cd/m^2) Y	X	y
D65	7.82	0.3128	0.3307
D40	7.62	0.3807	0.3835
D145	7.88	0.2637	0.2717
Red	7.41	0.341	0.2868
Green	7.48	0.2782	0.3815

C. Observers

Seven observers participated: 3 males, 4 females, age range 18–23 years, and all with normal color vision as verified by the Farnsworth–Munsell 100 Hue Test. Six observers were naïve to the purpose of the experiment; the seventh was the first author.

4. RESULTS

A. Pure Memory Shift and Constancy Shift

Here we define the matching error as the vector distance between the chromaticities of the matching and reference surfaces under the test illumination. The "pure memory shift" is the matching error when the test illumination is the same as the reference illumination (i.e., no illumination change) and the "constancy shift" is the matching error when the illumination changes. Figure 3 illustrates the mean matching errors for each reference patch in the seven saturation series, for each test illumination, averaged over all observers. Figure 4 shows the same results for all hue series.

In both figures, the black solid line between the black dot and triangle shows the size and the direction of the pure memory shift, i.e., the difference between the reference chromaticity and the matched chromaticity when there is no illumination change. The colored solid line represents the size and the direction of the constancy shift, i.e., the difference between the matched chromaticity and the chromaticity of the reference patch under the test illumination. Note that the direction of the constancy shift may be assessed relative to the direction of the pure memory shift by comparing each with the direction of the reference surface chromaticity under the test illumination relative to the test illumination's neutral point (dotted lines).

Table 2. Measured CIE Luv Lightness (L), Hue (H), and Saturation (S) Values under D65 Illumination for All Surfaces in the Seven Saturation Series, Together with the CIE Luv Color Differences (Delta E) between Each Test and Reference Patch[a]

	Saturation Series A				Saturation Series B				Saturation Series C			
Label	L	H	S	DeltaE	L	H	S	DeltaE	L	H	S	DeltaE
Ref.	72.99	6.25	0.57		69.86	0.73	0.94		65.95	5.91	0.66	
1	71.90	6.24	0.29	20.28	70.13	0.67	0.56	26.00	64.43	6.15	0.21	30.80
2	73.37	6.29	0.35	15.47	70.33	0.69	0.62	22.26	64.25	6.11	0.25	27.88
3	71.27	6.26	0.36	16.04	69.44	0.72	0.65	20.27	64.29	6.06	0.27	26.54
4	71.76	6.27	0.40	12.54	69.55	0.74	0.72	15.53	64.60	6.03	0.31	24.04
5	72.19	6.27	0.44	9.89	69.60	0.74	0.74	13.96	64.98	6.01	0.36	20.51
6	71.92	6.27	0.48	6.97	69.52	0.76	0.80	10.06	65.17	5.98	0.39	18.38
7	**73.31**	**6.27**	**0.54**	**2.22**	69.31	0.74	0.81	9.41	65.76	5.95	0.43	15.18
8	73.22	6.25	0.52	3.39	70.96	0.76	0.86	4.88	65.45	5.94	0.50	11.18
9	74.05	6.25	0.62	4.80	69.51	0.74	0.88	3.99	65.70	5.93	0.54	8.01
10	72.52	6.25	0.68	7.74	**69.23**	**0.74**	**0.93**	**1.27**	66.28	5.91	0.60	3.91
11	73.03	6.26	0.74	12.37	70.60	0.77	0.98	4.47	**66.27**	**5.91**	**0.65**	**0.61**
12	72.27	6.26	0.79	15.66	69.80	0.76	1.01	5.41	65.16	5.91	0.72	3.13
13	73.35	6.25	0.82	18.84	68.85	0.76	1.08	9.27	66.68	5.88	0.75	6.46
14	75.19	6.24	0.89	25.95	69.88	0.79	1.09	11.76	66.12	5.87	0.83	11.12
15	74.09	6.21	0.93	27.84	68.88	0.77	1.13	12.86	67.06	5.87	0.88	15.29
16	75.45	6.22	0.95	30.14	69.21	0.79	1.17	16.23	67.08	5.85	0.96	20.81

	Saturation Series D				Saturation Series E				Saturation Series F			
Label	L	H	S	DeltaE	L	H	S	DeltaE	L	H	S	DeltaE
Ref.	57.73	1.32	0.71		58.75	0.87	0.96		56.78	3.52	0.40	
1	55.78	1.26	0.33	22.72	60.24	0.92	0.22	43.19	55.86	3.67	0.14	15.05
2	56.78	1.33	0.34	21.71	57.22	0.87	0.36	35.83	56.35	3.71	0.17	13.43
3	56.30	1.36	0.41	18.00	56.98	0.87	0.41	33.09	56.29	3.62	0.22	10.47
4	58.29	1.36	0.43	15.98	56.54	0.87	0.46	30.47	56.64	3.60	0.26	8.12
5	57.65	1.29	0.45	15.08	57.46	0.87	0.52	26.55	57.29	3.57	0.29	6.20
6	57.41	1.33	0.52	11.15	57.24	0.89	0.62	20.98	56.70	3.55	0.34	3.49
7	58.66	1.41	0.54	9.90	58.29	0.86	0.66	17.94	**56.46**	**3.53**	**0.42**	**1.08**
8	58.85	1.39	0.57	7.96	58.06	0.85	0.73	14.07	56.86	3.52	0.48	4.58
9	57.49	1.33	0.58	7.66	60.82	0.87	0.78	9.20	56.54	3.50	0.51	6.15
10	58.13	1.36	0.66	3.09	57.47	0.89	0.78	11.69	56.54	3.49	0.58	10.12
11	**56.82**	**1.38**	**0.71**	**2.68**	57.85	0.84	0.85	7.45	56.73	3.48	0.61	11.95
12	57.36	1.38	0.76	3.65	57.64	0.84	0.90	4.93	57.14	3.49	0.64	13.89
13	57.34	1.42	0.76	4.97	**59.81**	**0.90**	**0.95**	**2.05**	57.12	3.48	0.67	15.61
14	56.18	1.41	0.85	8.00	57.32	0.86	1.02	2.58	56.30	3.47	0.74	19.02
15	56.16	1.40	0.90	10.35	57.91	0.85	1.02	3.03	55.51	3.46	0.81	22.37
16	55.81	1.42	0.96	13.57	58.17	0.87	1.05	4.71	55.34	3.46	0.82	22.79

	Saturation Series G					Saturation Series G, cont.			
Label	L	H	S	DeltaE	Label	L	H	S	DeltaE
Ref.	59.53	1.61	0.55		9	**58.44**	**1.67**	**0.56**	**2.25**
1	57.59	1.26	0.25	19.94	10	59.03	1.66	0.60	3.21
2	56.90	1.43	0.28	17.50	11	58.96	1.69	0.62	4.75
3	57.75	1.46	0.32	14.84	12	58.42	1.70	0.65	6.22
4	57.83	1.54	0.34	13.31	13	57.45	1.72	0.71	9.23
5	60.10	1.55	0.35	11.83	14	57.56	1.74	0.73	10.64
6	57.92	1.65	0.46	6.42	15	57.61	1.74	0.80	14.40
7	57.48	1.63	0.49	5.05	16	56.87	1.77	0.85	17.05
8	58.77	1.67	0.52	2.99					

[a]The best match to the reference surface is indicated in bold; note that slight variations in printing and measurement error contribute to a very small but nonzero color difference between the reference surface and the matching test surface under the test illumination.

Two conclusions are clear from inspecting the figures: (a) there is generally a substantial matching error even without an illumination change, i.e., a substantial pure memory shift; and (b) the size and the direction of the constancy shift depends profoundly on the size and direction of the pure memory shift along the constraint contours provided by the alternative chromaticities. For example, in the saturation series, under constant illumination, the matching errors tend to be in the direction of increasing saturation, as illustrated by the black arrows pointing away from the neutral point in Fig. 3. Likewise, under changing illumination, observers' matches are more saturated than the reference patch would be under the test illumination, regardless of the direction of illumination change (exceptions are the D and E series under Red illumination). We infer from this result that observers tend to remember the reference color as more saturated. A similar observation applies to the hue series shown in Fig. 4. Here, for different reference patches, although the matching chromaticity may occur in different directions along the contour of alternatives, the size and direction of the constancy shift closely resemble those of the pure memory shift.

In this experiment, perfect color constancy obtains when the observer selects the same patch under all test illuminations including D65, even if this patch differs from the original reference patch. In other words, an observer may display perfect color constancy despite imperfect color memory, provided changes in illumination do not affect that memory. In this case, the vectors representing the pure memory shifts (solid black lines) in Fig. 3 and Fig. 4 should lie parallel to the vectors representing

Table 3. Measured CIE Luv Lightness (L), Hue (H), and Saturation Values under D65 Illumination for All Six Hue Series, Together with the CIE Luv Color Differences (DeltaE) between Each Test and Reference Surface[a]

	Hue Series A				Hue Series B				Hue Series C			
Label	L	H	S	DeltaE	L	H	S	DeltaE	L	H	S	DeltaE
Ref.	71.11	5.94	0.55		65.95	6.18	0.43		64.89	3.90	0.19	
1	72.37	6.59	0.59	26.49	64.60	6.84	0.41	17.99	64.49	4.68	0.27	12.25
2	73.27	6.50	0.60	23.65	64.59	6.76	0.42	16.05	64.01	4.54	0.26	10.03
3	73.50	6.42	0.61	20.98	65.13	6.68	0.44	14.22	64.47	4.46	0.22	7.55
4	72.53	6.35	0.62	18.23	64.53	6.60	0.45	12.16	63.33	4.21	0.22	4.62
5	72.94	6.28	0.61	15.22	65.44	6.50	0.46	9.58	63.56	4.06	0.22	2.98
6	73.18	6.24	0.66	16.05	64.98	6.40	0.45	6.55	**63.67**	**3.89**	**0.21**	**1.61**
7	72.17	6.18	0.65	12.93	64.78	6.27	0.44	2.82	63.44	3.68	0.21	3.32
8	72.45	6.13	0.64	10.94	**64.46**	**6.17**	**0.42**	**1.99**	63.89	3.53	0.19	4.61
9	71.49	6.05	0.60	5.89	65.03	6.06	0.42	3.62	64.23	3.38	0.20	6.52
10	71.38	6.00	0.62	5.72	64.97	5.96	0.41	6.35	64.36	3.29	0.20	7.60
11	**70.55**	**5.94**	**0.58**	**1.89**	64.41	5.85	0.40	9.38	65.25	3.08	0.19	9.86
12	70.75	5.89	0.56	2.06	64.89	5.76	0.39	11.63	64.50	3.00	0.20	10.99
13	69.77	5.83	0.54	4.65	64.56	5.64	0.39	14.67	64.84	2.77	0.18	12.86
14	70.46	5.78	0.52	6.57	65.52	5.55	0.38	16.83	65.49	2.65	0.19	14.51
15	71.03	5.72	0.50	8.94	65.41	5.47	0.37	18.69	65.75	2.42	0.18	16.32
16	71.25	5.65	0.49	11.47	65.69	5.36	0.37	21.32	65.71	2.21	0.17	17.61

	Hue Series D				Hue Series E				Hue Series F			
Label	L	H	S	DeltaE	L	H	S	DeltaE	L	H	S	DeltaE
Ref.	57.78	6.45	0.65		59.49	2.83	0.39		57.51	5.14	0.40	
1	56.82	6.90	0.68	17.06	56.98	3.33	0.40	11.66	56.56	5.48	0.46	8.86
2	56.89	6.81	0.68	13.72	57.29	3.18	0.41	8.43	56.36	5.31	0.44	4.58
3	56.66	6.75	0.69	11.61	57.46	3.06	0.40	5.68	**55.85**	**5.18**	**0.42**	**1.96**
4	56.58	6.70	0.70	9.91	57.36	2.94	0.43	3.69	55.95	5.07	0.42	2.31
5	57.19	6.62	0.68	6.65	**57.84**	**2.81**	**0.40**	**1.72**	56.22	5.03	0.40	2.86
6	56.28	6.54	0.68	3.79	57.29	2.70	0.44	4.33	55.75	4.91	0.39	5.57
7	**55.83**	**6.45**	**0.68**	**1.99**	58.42	2.59	0.42	5.96	55.62	4.74	0.37	9.18
8	56.49	6.36	0.65	3.68	57.79	2.45	0.41	9.03	56.10	4.65	0.35	10.94
9	54.90	6.30	0.68	6.31	58.15	2.32	0.41	11.96	56.46	4.43	0.32	15.04
10	55.02	6.19	0.64	10.21	58.22	2.19	0.41	14.87	55.14	4.25	0.30	18.15
11	55.47	6.10	0.65	13.22	58.06	2.05	0.43	18.44	55.47	4.05	0.29	21.21
12	55.56	6.00	0.67	16.95	58.00	1.92	0.42	20.98	56.42	3.95	0.26	22.24
13	55.96	5.91	0.65	19.95	57.86	1.81	0.43	23.57	55.74	3.78	0.25	24.34
14	55.70	5.83	0.65	22.75	58.22	1.57	0.44	28.85	56.64	3.60	0.22	25.84
15	55.41	5.74	0.68	26.37	58.17	1.41	0.48	33.54	56.70	3.30	0.22	28.95
16	55.78	5.68	0.69	28.75	58.12	1.33	0.50	35.91	56.87	3.11	0.21	30.26

[a]The best match to the reference surface is indicated in bold; note that slight variations in printing and measurement error contribute to a very small but nonzero color difference between the reference surface and the matching test surface under the test illumination.

Table 4. Estimated Munsell Color Notations of Reference Surfaces for All Seven Saturation (Sat.) Series and Six Hue Series

Reference	A	B	C	D	E	F	G
Sat. Series	2.5GY	10YR 6/6	7.5GY 6/6	10R 5/4	7.5R	10B 5/2	2.5R 5/4
Hue Series	7.5GY	5GY 6/4	7.5BG 6/2	10Y 5/4	2.5P	5G 5/4	

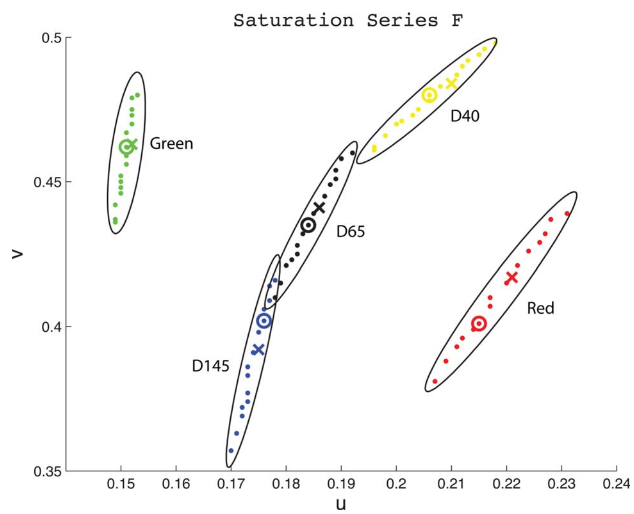

Fig. 1. (Color online) Experimental stimuli and one observer's results for saturation series F plotted on a CIE uv diagram. The markers within each ellipse indicate the reference and test patch chromaticities under a test illumination. The cross represents the reference patch chromaticity under each test illumination; the dots represent the chromaticities of the available alternatives in the test plate under the test illumination; and the circle represents the surface selected by the observer.

the constancy shifts (solid colored lines), and their magnitudes should be identical (assuming the chromaticity space is entirely uniform).

Visual inspection of Figs. 3 and 4 suggests that although the overall degree of color constancy is high, certain surfaces under certain illuminations may possess greater color constancy than others. For example, for saturation series A, color constancy under the Red and Green illuminations is better than under D40 (yellow) and D145 (blue). Table 5 illustrates the size of the mean and standard deviation of the mean matching errors under all illuminations and averaged across all seven observers. An N-way analysis of variance (ANOVA) confirms that the size of the matching error is significantly affected by illumination ($p=0.0001$) and reference surface ($p<0.0001$), and that the interaction between illumination and reference surface is also significant ($p=0.0064$). To analyze color constancy quantitatively, it is therefore essential to develop a simple mathematical measure that represents the degree of successive color constancy for distinct conditions.

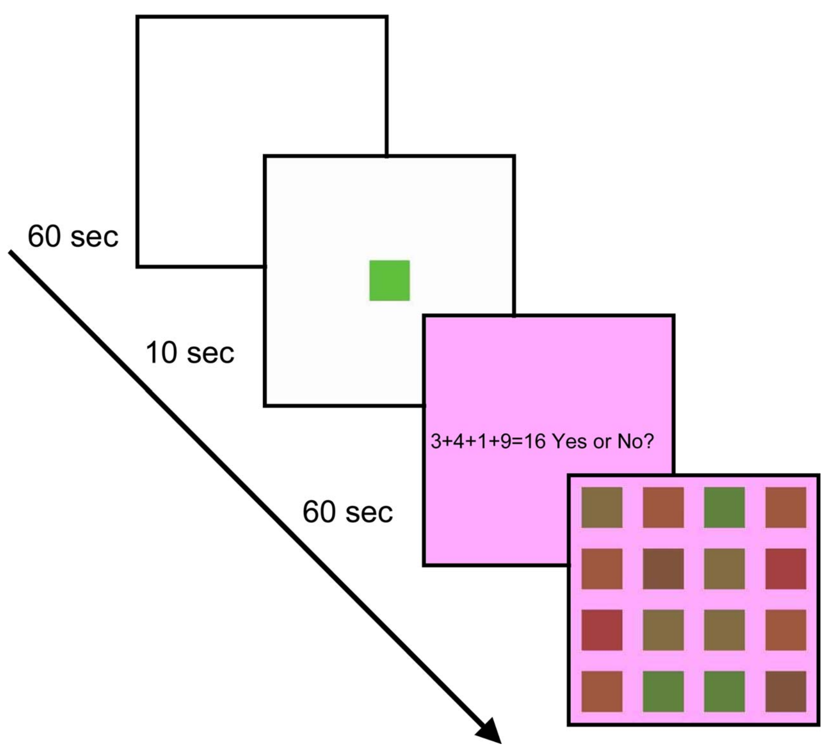

Fig. 2. (Color online) Experimental protocol for one memory trial. Observer first preadapts to the reference illumination for 60 s, second, views the reference plate under the reference illumination for 10 s; third, adapts to the test illumination for 60 s while performing an arithmetic task, and, fourth, views the test plate under the test illumination and is allowed unlimited time to select the alternative that best matches the remembered reference patch.

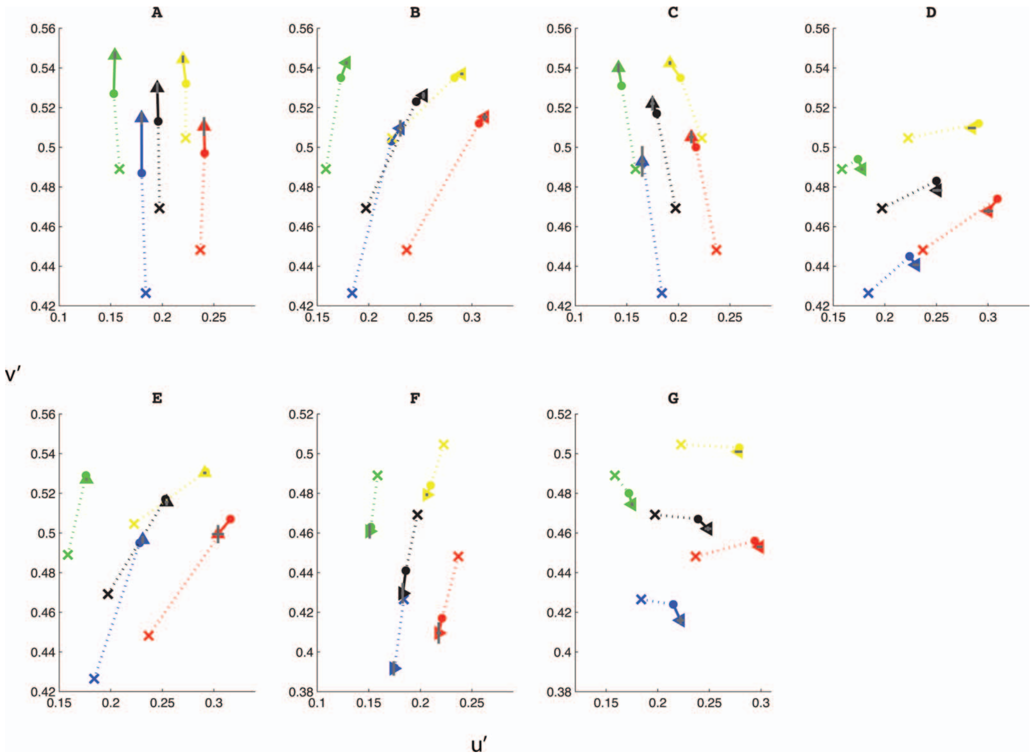

Fig. 3. Chromaticities of mean matching surfaces (triangles), the reference patches (dots), and the illuminations (crosses) for seven saturation series under the five test illuminations plotted in CIE u′v′ chromaticity diagrams. The SDM values of the mean matching chromaticities are illustrated by gray crosses over the triangles: horizontal cross bar; SDM of u′; vertical cross bar; SDM of v′. Each panel represents the results for one reference patch. The marker color indicates the type of test illumination: black, D65; blue, D145; yellow, D40; green, Green; red, Red. The solid line connects the mean matching chromaticity with the reference patch chromaticity under the test illumination, indicating the direction of the matching error shift. The black solid line corresponds to the pure memory shift S_m, the colored solid lines correspond to the constancy shifts $\vec{S}_c$, and the distance between the black and colored dots corresponds to the physical shift $\vec{S}_p$ in Eq. (2). The dotted line connects the neutral point of the test illumination with the reference patch chromaticity under the test illumination.

B. Color Constancy Index

There are two main drawbacks of using the BR as a measure of successive color constancy: (a) it does not incorporate color memory; and (b) it does not take into account the direction of the perceptual shift (the matching error in our terminology). The latter has often been overlooked even in traditional simultaneous color constancy studies [34]. The BR calculation implicitly assumes that the perceptual shift is constrained to occur along the direction of the physical shift, i.e., the direction in which surface chromaticity changes under changing illumination. The primary (or sole) cause of imperfect color constancy is implicitly assumed to be a perceptual shift opposite in direction to the physical shift, in which the observer attempts to match the reference chromaticity rather than the chromaticity of the reference patch under the test illumination — i.e., an attempt to make a "chromaticity" match instead of a "surface" match [2]. In actuality, though, the observer is often allowed to match colors along any direction, and imperfect color constancy may therefore result from errors of different types, including overcompensation for the illumination change. As Fig. 5 illustrates, different perceptual shifts (b1, b2, and b3) may result in the same BR, although only for b1 does the subject attempt to make a chromaticity match.

Here we introduce a new color constancy index (CCI) for successive color constancy that not only incorporates color memory, but also embodies the direction of the matching error. Assuming the observer has complete freedom of choice for the color match, the CCI is computed as

$$\mathrm{CCI} = 1 - \frac{(\vec{S}_c - \vec{S}_m) \cdot (-\vec{S}_p)}{\|\vec{S}_p\|}, \tag{2}$$

where $\vec{S}_c$ represents the constancy shift, $\vec{S}_m$ the pure memory shift, and $\vec{S}_p$ the physical shift of the stimulus under an illumination change, all vector quantities that encode size and direction. The difference between the constancy shift and pure memory shift is measured as the vector difference $\vec{S}_c - \vec{S}_m$, as shown in Fig. 6(a). The dot product of this difference vector with $-\vec{S}_p$ provides the component of the color match that derives from imperfect color constancy in the direction of a chromaticity match.

Therefore, if the constancy shift is entirely consistent with the pure memory shift (i.e., $\vec{S}_c = \vec{S}_m$), then CCI=1 and color constancy is perfect [Fig. 6(b)]; if the observer makes no error in the pure memory match ($\vec{S}_m = 0$), but makes only a chromaticity match under changing illumination ($\vec{S}_c = -\vec{S}_p$), then CCI=0 and there is no color con-

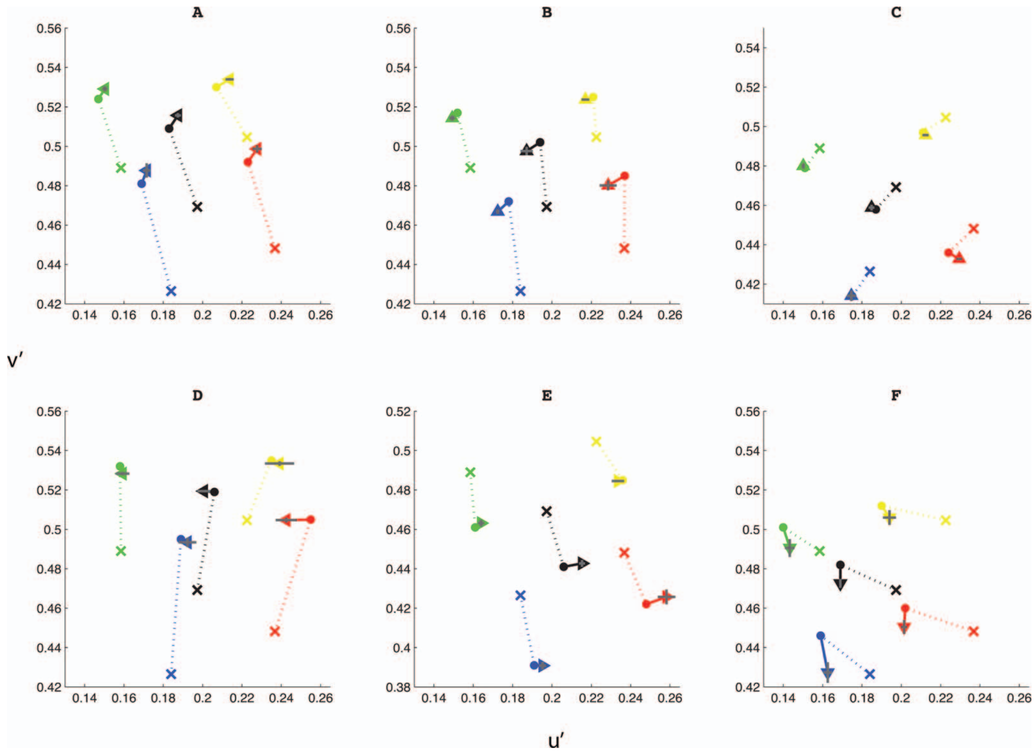

Fig. 4. The mean matching chromaticities (triangles), the reference patch chromaticities (dots), and the illumination chromaticities (crosses) for six hue series under five test illuminations plotted in CIE u′v′ chromaticity diagrams. The SDM values of the mean matching chromaticities are illustrated by gray crosses over the triangles: horizontal bar, SDM of u, vertical bar, SDM of v. Each panel represents the results for one reference patch. The marker color indicates the type of test illumination: black, D65; blue, D145; yellow, D40; green, Green; red, Red. The solid line connects the mean matching chromaticity with the reference surface chromaticity under the test illumination, indicating the direction of the memory shift. The black solid line corresponds to the pure memory shift $\vec{S}_m$, the colored solid lines correspond to the constancy shifts $\vec{S}_c$, and the distance between the black and colored dots corresponds to the physical shift $\vec{S}_p$ in Eq. (2). The dotted line connects the test illumination chromaticity with the reference patch chromaticity under that illumination, illustrating the position of the reference patch chromaticity with respect to the neutral point under that illumination.

stancy [Fig. 6(c)]; if the observer makes a perfect match under changing illumination ($\vec{S}_c=0$), but makes an error in memory under constant illumination, such that the pure memory shift equals the physical shift ($\vec{S}_m=\vec{S}_p$), then the observer does not evidence color constancy, and the CCI indicates this fact with a value of zero [Fig. 6(d)]. Note that under these definitions, $\mathrm{BR}=1-(\|\vec{S}_c\|/\|\vec{S}_p\|)$ and therefore yields the same value for color constancy only in the case of Fig. 6(c).

Equation (2) assumes that there is no restriction on the matching surface choices so that the effect of the illumination change may be computed without bias. In this ex-

Table 5. Mean Matching Errors and Their Standard Deviation of Mean (SDM) Values for All Color Series under All Five Illuminations Averaged across All Seven Observers, Reported in CIE Luv ΔE Units

Series	D65	D145	D40	Red	Green
Sat. A	16.57 (3.12)	26.74 (3.59)	12.65 (2.03)	13.12 (4.24)	19.29 (2.12)
Sat. B	7.18 (1.63)	12.84 (1.71)	6.96 (1.42)	8.25 (1.59)	7.13 (0.81)
Sat. C	9.10 (2.26)	14.25 (4.28)	10.90 (1.46)	8.38 (1.91)	9.27 (2.16)
Sat. D	8.23 (1.59)	6.70 (1.18)	7.22 (2.40)	10.47 (2.82)	4.67 (0.40)
Sat. E	4.32 (1.21)	4.33 (0.50)	3.39 (0.82)	14.42 (5.27)	1.77 (0.13)
Sat. F	11.21 (2.51)	6.28 (0.95)	4.28 (0.49)	10.31 (2.24)	5.10 (1.81)
Sat. G	7.91 (2.39)	9.94 (0.99)	7.22 (0.96)	6.37 (1.22)	4.44 (0.82)
Hue A	7.98 (1.65)	10.85 (1.87)	7.67 (1.85)	8.72 (2.29)	6.23 (1.73)
Hue B	8.30 (2.71)	6.84 (1.18)	4.84 (1.10)	9.91 (3.49)	4.51 (1.10)
Hue C	3.89 (1.13)	6.27 (1.48)	3.23 (0.83)	5.41 (0.95)	3.10 (0.85)
Hue D	6.89 (1.41)	8.80 (1.77)	13.07 (2.39)	10.43 (3.69)	7.38 (0.68)
Hue E	7.66 (1.43)	5.04 (1.35)	5.52 (1.39)	10.96 (3.40)	5.23 (0.90)
Hue F	7.77 (1.27)	14.84 (4.08)	7.93 (2.74)	7.79 (2.29)	9.22 (3.42)

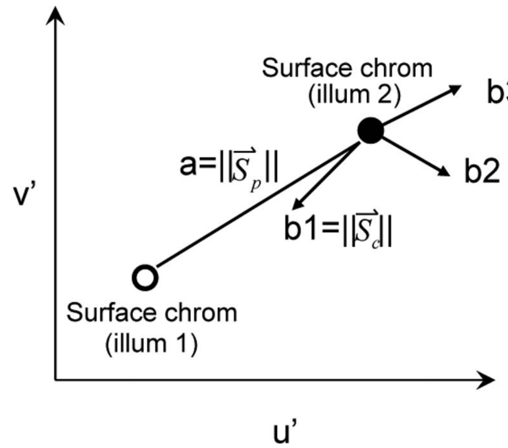

Fig. 5. Examples of color matches and their consequences for BR calculations in CIE $u'v'$ space. 'a' represents the magnitude of the physical shift $\vec{S}_p$ under the change from illumination 1 to illumination 2; 'b1', 'b2', and 'b3' represent the respective magnitudes of three possible perceptual shifts $\vec{S}_c$, each of which generates the same BR value.

periment, though, the chromaticities of the alternative surfaces approximately vary in saturation or hue only along a one-dimensional contour. The relationship between the direction of the alternatives' contour and the direction of the illumination change varies with reference color and test illumination, and therefore may introduce misleading variations in the CCI. We thus modify Eq. (2) for this particular experiment:

$$\mathrm{CCI} = 1 - \frac{\|\vec{S}_c - \vec{S}_m\| * d}{\|\vec{S}_p\|}, \tag{3}$$

where d is a directional factor that assumes the value of 1 or -1, depending on the relative directions of $\vec{S}_c$ and $\vec{S}_m$. If the two shifts share a directional component, and $\|\vec{s}_c\| < \|\vec{s}_m\|$, d is set to equal -1, representing better color constancy than color memory, and $\mathrm{CCI} > 1$. In all other conditions, $d=1$ and $\mathrm{CCI} \leq 1$, indicating imperfect color constancy.

Table 6 quantifies the experimental results in terms of CCI. Across all four changes in illumination, the CCI varies around 0.9, revealing near-perfect color constancy within the limits of color memory. These results imply that changes in illumination have a very small effect on the constancy shift, which instead is largely determined

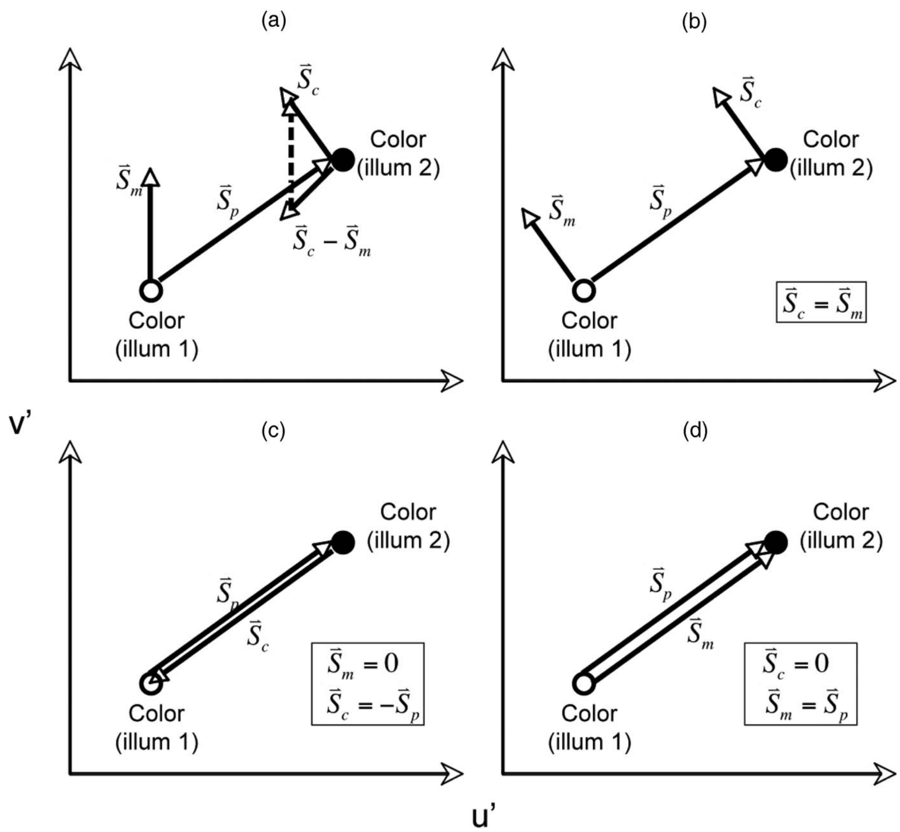

Fig. 6. Examples of color matches and their consequences for CCI values. For all panels, the illumination changes from 'illum 1' to 'illum 2'. (a) $\vec{S}_p$ illustrates the surface chromaticity's physical shift under changing illumination in the color space (corresponding to the 'physical shift' in the BR); $\vec{S}_m$ illustrates the pure memory shift under illumination 1; $\vec{S}_c$ represents the constancy shift under illumination 2 (and corresponds to the 'perceptual shift' in the BR); and $\vec{S}_c - \vec{S}_m$ is the vector representing the difference between the constancy shift and the pure memory shift. (b) When $\vec{S}_c = \vec{S}_m$, the illumination change has no effect on the color choice, and CCI=1. (c) If the observer makes no mistake in the memory match but selects the chromaticity under illumination 1 as the constancy match, then there is no color constancy and CCI=0. (d) If the observer picks the chromaticity under illumination 2 as a memory match but makes no mistake in the constancy match, then the illumination change again has a full impact on the color choice and CCI=0.

Table 6. Mean CCI Results for All Color Series under Four Illumination Changes Averaged across Seven Observers[a]

Series	D145	D40	Red	Green
Sat. A	0.65	1.07	1.08	0.95
Sat. B	0.89	0.98	0.92	0.96
Sat. C	0.78	0.79	1.03	0.91
Sat. D	0.96	0.86	0.77	0.94
Sat. E	1.00	0.90	0.70	0.95
Sat. F	1.09	1.13	0.78	1.00
Sat. G	0.85	0.78	1.05	1.09
Hue A	0.80	0.77	0.92	0.88
Hue B	1.03	1.13	0.95	1.08
Hue C	0.81	0.91	0.79	1.01
Hue D	1.15	0.93	0.90	0.81
Hue E	1.11	0.86	0.85	0.88
Hue F	0.75	0.86	1.00	0.95
Mean All Sat.	0.89	0.93	0.90	0.97
Mean All Hue	0.94	0.91	0.90	0.94

[a]The final two rows give the overall mean CCI results averaged over all saturation series and hue series.

by the pure memory shift. For comparison, we tabulate the BR values for the same set of matching results in Table 7.

Table 7 demonstrates that the computed BR values are generally smaller than the CCI ($p<0.0001$). For example, for Saturation Series A under D145 illumination, the BR value is near zero, indicating almost no color constancy at all, whereas the CCI is approximately 0.65, indicating a respectable level of color constancy. Further inspection of the results in Fig. 3 reveals that the relatively large matching errors for Saturation Series under D145 are predominantly due to the observers' remembering the color as more saturated. This comparison highlights the inadequacy of the BR as a measure for successive color constancy and illustrates the need to separate the components of memory and illumination compensation in successive asymmetric matching tasks.

Table 7. Mean BR Indices for All Color Series under Illumination Changes Averaged across Seven Observers[a]

	D145	D40	Red	Green
Sat. A	0.09	0.61	0.71	0.57
Sat. B	0.50	0.81	0.86	0.88
Sat. C	0.43	0.57	0.76	0.73
Sat. D	0.79	0.81	0.78	0.91
Sat. E	0.81	0.92	0.73	0.97
Sat. F	0.83	0.88	0.66	0.83
Sat. G	0.72	0.85	0.86	0.91
Hue A	0.64	0.74	0.78	0.83
Hue B	0.78	0.85	0.76	0.88
Hue C	0.84	0.92	0.85	0.92
Hue D	0.60	0.48	0.74	0.81
Hue E	0.88	0.88	0.69	0.87
Hue F	0.48	0.71	0.73	0.66
Mean All Sat.	0.60	0.78	0.76	0.83
Mean All Hue	0.70	0.76	0.76	0.83

[a]The final two rows give the overall mean BR results averaged over all saturation series and hue series.

5. DISCUSSION

A. Color Constancy Index

In this experiment, we used the simplified version in Eq. (3) to compute CCI to accommodate the fact that the alternative surfaces have been chosen so that their chromaticities vary approximately along a single dimension in the chromaticity plane. Fig. 1 shows the results for saturation series F—a "blue" color—which illustrate the need for the simplified version of the CCI. Here the 16 alternative chromaticities differ only in saturation and vary along the blue–yellow axis. (Saturation for this color generally increases as v' decreases). When the illumination changes from D65 to D40 (neutral to "yellowish"), the observer's match shifts in a more "bluish" direction (compared with the match under neutral conditions), corresponding to a more saturated color. This error is consistent with imperfect color constancy in the form of undercompensation for the illumination change. When the illumination changes from D65 to D145 (neutral to "bluish"), the observer matches the color as more "yellowish" (less saturated), again consistent with undercompensation for the illumination change. Accordingly, if we employ Eq. (2) to compute the CCI under D40 and D145, as the direction of the matching shift $(\vec{S}_c-\vec{S}_m)$ aligns with the direction of the illumination change, the dot product between the matching shift and $\vec{S}_p$ will be maximized, and deviations from constancy will be appropriately captured.

For the Red and Green illumination conditions, the directions of the illumination shifts $(\vec{S}_p)$ are almost orthogonal to the directions of the matching shifts $(\vec{S}_c-\vec{S}_m)$, so the dot product between them will tend to underrepresent the matching error even when it is large, as in the case of the Red illumination. It is thus inappropriate to compute CCI with Eq. (2) here. For successive color constancy experiments in which multidimensional color matches may be made, Eq. (2) provides a better measure for color constancy than Eq. (3).

B. Is Color Constancy Perfect?

The traditional Brunswik ratio index (BR) computes the degree of constancy between the limits of a perfect surface reflectance match and a chromaticity match and ascribes perfect color constancy to the observer only when he makes no error in his surface reflectance match. The CCI that we introduce here, though, tolerates mistakes and accepts that observers might not be perfect at the color matching task irrespective of illumination and context changes. The CCI ascribes perfect color constancy to the observer provided that his matching error is not influenced by changes in illumination. In other words, the BR index measures the precision of color constancy with respect to the absolute surface, while the CCI measures color constancy relative to the limitations imposed by color perception and memory.

The extent to which our visual system possesses color constancy has been extensively investigated. Most studies deliver the same message: color constancy is significant, but not perfect. The highest BR index reported from asymmetric color matching experiments is 0.77 [34], lower than the typical CCI measured in this experiment.

Many traditional studies define color constancy as the ability of the visual system to eliminate the component due to the illumination in the light reaching the eye [28]. Perfect color constancy would thus entail that an object viewed under one illumination would appear exactly the same under another illumination, and our visual system would be unable to detect the change in illumination. In the real world, though, we are usually able to detect changes in illumination [35], and pure appearance matches under changing illumination have yielded much poorer color constancy than object matches, when the matched surface is accepted as the same object as the reference patch under different illuminations [2,3].

Therefore, from a more natural perspective, we may argue that the ultimate purpose of color constancy is to aid object recognition—to prevent an object from being incorrectly identified as a different object due to variations in illumination [36–38]. Thus color constancy may be considered perfect provided the object has not been falsely identified, or, in other words, the chromaticity shift resulting from an illumination change should not prevent an object from being identified by its color.

In the real world, to recognize an object accurately, the visual system must tolerate the errors introduced by imperfect color memory. Therefore, there must be a certain range of chromaticity shifts within which the object's color may still be identified as the same. In the experiment described here, we have shown that this degree of tolerance is little affected by changes in illumination. We therefore conclude that color constancy is almost perfect, or to avoid confusion with other definitions, we say that color constancy is as good as memory allows.

C. Further Discussion

When an observer views an object, the light that reaches the observer's retina may be expressed as the function $S = I * R$, where S represents the light the observer receives, I represents the spectrum of the illumination, and R represents the object's surface reflectance. Jin and Shevell's experiment revealed that color recalled from memory is based on an inferred spectral reflectance of the surface (R) rather than retinal cone signals (S) [9]. To remember color as surface reflectance, the reflectance (R) must first be estimated from S, and as Maloney has shown [39], calculating the surface reflectance from a limited set of cone signals may create errors.

Therefore, even without any change in illumination, color memory should embed the errors created by insufficient estimation of R from S, and the pure memory shift should contain two components: the error derived from computational errors in the predicted surface reflectance, and the error derived from the decaying memory. The former component of the pure memory shift has been almost entirely overlooked in color memory studies, most of which assume that the memory shift derives from decaying memory only.

We speculate that some well-established color memory effects, such as the increase in saturation of remembered colors, may also be due to inadequate computation of the surface reflectance. This hypothesis is partially supported by the results of de Fez *et al.* [15] from an asymmetric color matching experiment in which the matched color, when presented simultaneously under a different illumination, was found to be more saturated than the reference color. More systematic experiments are needed to verify the speculation explicitly.

Methods to study color memory are well established. If the deficiency in remembering colors is due to inadequate recovery of surface reflectance, then these "tried and tested" color memory experiments may be employed as an empirical platform for further studies in color constancy. Computational color constancy studies propose several methods by which surface reflectance may be recovered from the retinal cone signals [36]; conversely, color memory studies might help to test these models empirically.

D. Implications

The role of memory in color constancy has been underrepresented in recent successive matching studies. In this study, we implemented a typical successive color constancy paradigm and separated the effect of memory and illumination changes. By factoring out the effect of memory, we found very high levels of constancy. Our results suggest that the limitations of color memory must be considered in successive color constancy studies and everyday constancy tasks.

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